

RF AM Stabilization

T0900198-v1
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Theory of Operations

The amplitude stabilization circuit requires a low noise RF detector. The presented design uses a combination of series and shunt diode detectors in a differential arrangement to effectively quadruple the response. A parallel chain of diodes is used to both compensate for temperature drifts and to remove a bias. Under nominal RF load this detector then has zero output and directly be used in compensation network to control a variable RF attenuator ahead of the detector. A relatively high bias current is applied to the diodes to

Specifications

TBD.

Setup

```
Needs["BarCharts`"]; Needs["Histograms`"]; Needs["PieCharts`"];  
Needs["ErrorBarPlots`"]; Needs["PlotLegends`"];  
Needs["Controls`LinearControl`"]  
  
$TextStyle = {FontFamily -> "Helvetica", FontSize -> 13};  
  
plotopt = PlotStyle -> {{Thickness [0.007], RGBColor [1, 0, 0]},  
                        {Thickness [0.007], RGBColor [0, 0, 1]},  
                        {Thickness [0.007], RGBColor [0.1, 0.7, 0.2]},  
                        {Thickness [0.007], RGBColor [0.5, 0.5, 0.2]}};
```

Common Definitions

```
FromdB[x_] := 10x/20  
FromdBc[x_] := 10-x/20  
  
NoiseLevelBottom[f_] := FromdBc[175]
```

Model

Parallel and Serial Impedance

```

par[r1_, r2_] :=  $\frac{1}{\frac{1}{r1} + \frac{1}{r2}}$ 

par[r1_, r2_, r3_] :=  $\frac{1}{\frac{1}{r1} + \frac{1}{r2} + \frac{1}{r3}}$ 

ser[r1_, r2_] := r1 + r2
ser[r1_, r2_, r3_] := r1 + r2 + r3

```

Pole/zero

```

pole[f_, f0_] :=  $\frac{1}{1 + i \frac{f}{f0}}$ 

zero[f_, f0_] :=  $1 + i \frac{f}{f0}$ 

```

Transfer Function of an OpAmp

This function computes the transfer function of an idealized OpAmp circuit

g: +1 for non-inverting configuration or -1 for inverting configuration, 0 for differential configuration

z2: Impedance in feedback path [Ohm]

z1: Impedance of input path (inverting) or impedance to ground (non-inverting) [Ohm]

```

OpAmp[g_, z1_, z2_] :=
  Which[g > 0, 1 +  $\frac{z2}{z1}$ , g < 0,  $\frac{z2}{z1}$ , True,  $\frac{z2}{z1}$ ]

```

Noise of an OpAmp

This function computes the equivalent input noise of an OpAmp circuit

g: +1 for non-inverting configuration or -1 for inverting configuration, 0 for differential configuration

z1: Impedance of input path (inverting) or impedance to ground (non-inverting) [Ohm]

z2: Impedance over feedback path [Ohm]

en: voltage noise [Volt]

in: current noise [Ampere]

```

FourKT = 1.62*^-20; (* V^2/Hz/Ohm; room temperature 20C*)
OpAmpNoise[g_, z1_, z2_, en_, in_] :=
Which[g > 0, If[z1 == Infinity,  $\sqrt{en^2 + \text{FourKT Abs}[z2] + (\text{in Abs}[z2])^2}$ ,
 $\sqrt{en^2 + \text{FourKT Abs}[\text{par}[z1, z2]] + (\text{in Abs}[\text{par}[z1, z2]])^2}$ ],
g < 0,  $\sqrt{\left(\text{Abs}\left[1 + \frac{z1}{z2}\right]^2 en^2 + \text{Abs}[z1]^2 \left(\text{in}^2 + \text{Abs}\left[\frac{\text{FourKT}}{z1}\right] + \text{Abs}\left[\frac{\text{FourKT}}{z2}\right]\right)\right)}$ ,
True,  $\sqrt{\left(\text{Abs}\left[1 + \frac{z1}{z2}\right]^2 en^2 + 2 \text{Abs}[z1]^2 \left(\text{in}^2 + \text{Abs}\left[\frac{\text{FourKT}}{z1}\right] + \text{Abs}\left[\frac{\text{FourKT}}{z2}\right]\right)\right)}$ ]

```

Flicker Noise: The variable \$Flicker determines if flicker noise is added or not. It can also be explicitly specified with the option Flicker.

```

$Flicker = True;
Clear[OpAmpNoiseFlicker];
Options[OpAmpNoiseFlicker] = {Flicker => $Flicker};
OpAmpNoiseFlicker[f_, fknee_, opts___] :=

If[Flicker /. {opts} /. Options[OpAmpNoiseFlicker],  $\sqrt{\frac{\text{fknee}}{f} + 1}$ , 1]

OpAmpNoiseFlicker[f_, fknee_, floor_, opts___] := floor OpAmpNoiseFlicker[f, fknee, opts]

```

OpAmp Parameters

```

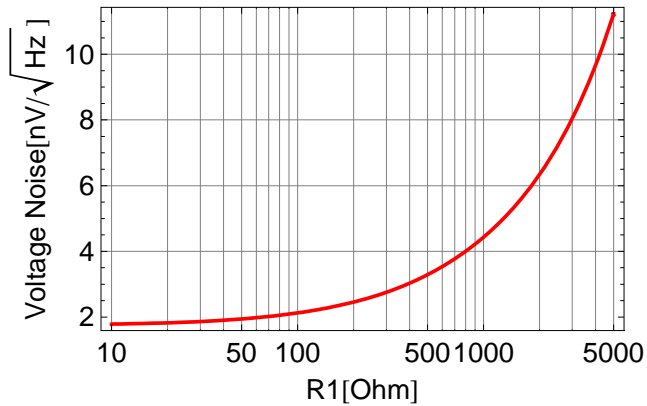
Clear[AD829, OP27]
AD829[f_] := {s → 2 π i f, en → enAD829, in → inAD829,
  enfloor → enfloorAD829, infloor → infloorAD829} //.
{enAD829 → OpAmpNoiseFlicker[f, ekneeAD829, enfloorAD829],
 inAD829 → OpAmpNoiseFlicker[f, ikneeAD829, infloorAD829],
 ekneeAD829 → 50, ikneeAD829 → 100, (*guess*)
 enfloorAD829 → 1.7*^-9, infloorAD829 → 1.5*^-12};
OP27[f_] := {s → 2 π i f, en → enOP27, in → inOP27,
  enfloor → enfloorOP27, infloor → infloorOP27} //.
{enOP27 → OpAmpNoiseFlicker[f, ekneeOP27, enfloorOP27],
 inOP27 → OpAmpNoiseFlicker[f, ikneeOP27, infloorOP27],
 ekneeOP27 → 2.7, ikneeOP27 → 140,
 enfloorOP27 → 3.0*^-9, infloorOP27 → 0.4*^-12};
LT1028[f_] := {s → 2 π i f, en → enLT1028, in → inLT1028,
  enfloor → enfloorLT1028, infloor → infloorLT1028} //.
{enLT1028 → OpAmpNoiseFlicker[f, ekneeLT1028, enfloorLT1028],
 inLT1028 → OpAmpNoiseFlicker[f, ikneeLT1028, infloorLT1028],
 ekneeLT1028 → 3.5, ikneeLT1028 → 250,
 enfloorLT1028 → 0.85*^-9, infloorLT1028 → 1*^-12};
LT1128[f_] := {s → 2 π i f, en → enLT1128, in → inLT1128,
  enfloor → enfloorLT1128, infloor → infloorLT1128} //.
{enLT1128 → OpAmpNoiseFlicker[f, ekneeLT1128, enfloorLT1128],
 inLT1128 → OpAmpNoiseFlicker[f, ikneeLT1128, infloorLT1128],
 ekneeLT1128 → 3.5, ikneeLT1128 → 250,
 enfloorLT1128 → 0.85*^-9, infloorLT1128 → 1*^-12};
AD797[f_] := {s → 2 π i f, en → enAD797, in → inAD797,
  enfloor → enfloorAD797, infloor → infloorAD797} //.
{enAD797 → OpAmpNoiseFlicker[f, ekneeAD797, enfloorAD797],
 inAD797 → OpAmpNoiseFlicker[f, ikneeAD797, infloorAD797],
 ekneeAD797 → 50, ikneeAD797 → 100, (*guess*)
 enfloorAD797 → 0.9*^-9, infloorAD797 → 2*^-12};
LT1012[f_] := {s → 2 π i f, en → enLT1012, in → inLT1012,
  enfloor → enfloorLT1012, infloor → infloorLT1012} //.
{enLT1012 → OpAmpNoiseFlicker[f, ekneeLT1012, enfloorLT1012],
 inLT1012 → OpAmpNoiseFlicker[f, ikneeLT1012, infloorLT1012],
 ekneeLT1012 → 2.5, ikneeLT1012 → 120, (*guess*)
 enfloorLT1012 → 14*^-9, infloorLT1012 → 6*^-15};

```

Examples (AD829)

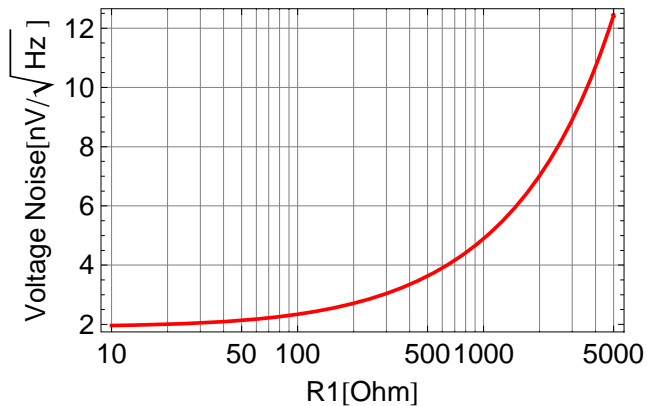
Non-Inverting configuration: input noise w/ gain of 10 as function of r1

```
LogLinearPlot[1*^9 OpAmpNoise[+1, r, 9 r, en, in] /. AD829[1000],
  {r, 10, 5000}, FrameLabel -> {"R1[Ohm]", "Voltage Noise[nV/√Hz]"}, Frame -> True,
  GridLines -> Automatic, PlotStyle -> {Thickness [0.007], Red}, BaseStyle -> $TextStyle]
```



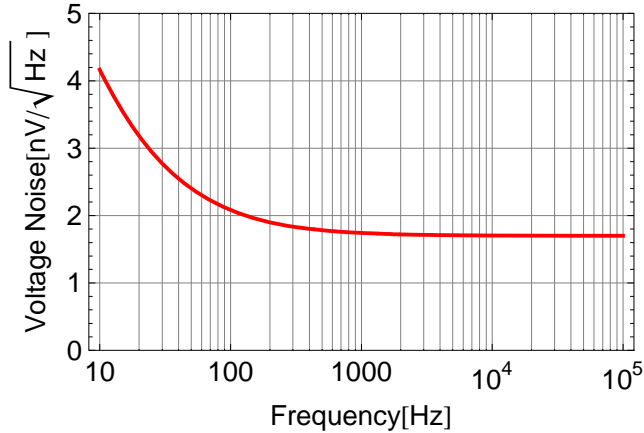
Inverting configuration: input noise w/ gain of 10 as function of r1

```
LogLinearPlot[1*^9 OpAmpNoise[-1, r, 10 r, en, in] /. AD829[1000],
  {r, 10, 5000}, FrameLabel -> {"R1[Ohm]", "Voltage Noise[nV/√Hz]"}, Frame -> True,
  GridLines -> Automatic, PlotStyle -> {Thickness [0.007], Red}, BaseStyle -> $TextStyle]
```



Input voltage noise with flicker.

```
LogLinearPlot[1*^9 en /. AD829[f], {f, 10, 1*^5},
  FrameLabel -> {"Frequency[Hz]", "Voltage Noise[nV/√Hz]"}, Frame -> True, PlotRange -> {0, 5},
  GridLines -> Automatic, PlotStyle -> {Thickness[0.007], Red}, BaseStyle -> $TextStyle]
```



Series Product of OpAmps

Computes the transfer function of several OpAmps circuits in series.

```
OpAmpProduct[t_, m_] := Product[t[i], {i, m}]
```

Computes the equivalent input noise of several OpAmps circuits in series.

```
NoiseSum[prev_, {t_, n_}] := √(prev2 + n2 Abs[t])
OpAmpNoiseProduct[t_, n_, m_] :=  $\frac{\text{Fold}[\text{NoiseSum}, 0, \text{Table}[\{t[i], n[i]\}, \{i, m\}]]}{\text{Abs}[\text{OpAmpProduct}[t, m]]}$ 
```

Spectrum Math

Propagate noise spectrum

```
SpecProp[prev_, t_] := {#[[1]], Abs[t /. s -> 2. π #[[1]] #[[2]]] & /@ prev}
SpecProp[noise_, t_, m_] := FoldList[SpecProp, noise, Table[t[i], {i, m}]]
```

RMS of spectrum

```
Clear[SpecRMS];
SpecRMS[l_List?(MatrixQ[#, NumberQ] &)] := Block[{i, sqr = 0},
  For[i = 1, i < Length[l], ++i,
    sqr += (l[[i + 1, 1]] - l[[i, 1]])  $\left(\frac{l[[i, 2]] + l[[i + 1, 2]]}{2}\right)^2$ ;
  √[sqr]
```

Integrated RMS spectrum

```

Clear[RMSSpec];
RMSSpec[l_List?(MatrixQ[#, NumberQ] &), dir_:(-1)] := Block[{i, sqr = 0, r = N[l]},
  If[dir >= 0,
    For[i = 2, i <= Length[l], ++i,
      r[[i, 2]] =  $\sqrt{r[[i-1, 2]]^2 + r[[i, 2]]^2 (r[[i, 1]] - r[[i-1, 1]])}$  ],
    For[i = Length[l] - 2, i >= 1, --i,
      r[[i, 2]] =  $\sqrt{r[[i+1, 2]]^2 + r[[i, 2]]^2 (r[[i+1, 1]] - r[[i, 1]])}$  ]];
r]

```

Shottky Diode Model

We are using the noise model of a HSMS-281K. See data sheet and application note 956-3.

■ Parameters

```

HSMS281Param =
  {BV → 25, CJ → 1.1*^-12, EG → 0.69, IBV → 1*^-5, IS → 4.8*^-9, n → 1.08, RS → 10, T → 273.15 + 25};
ShottkyParam = HSMS281Param;

8.33*^-5 n T /. HSMS281Param

0.0268228

```

■ Resistance Model

```

RJ[i_] :=  $\frac{8.33*^-5 n T}{IS + i}$  /. ShottkyParam
RV[i_] := RJ[i] + RS /. ShottkyParam
ZShottky[i_, f_] := ser[RS, par[RJ[i],  $\frac{1}{2 \pi i f CJ}$ ]] /. ShottkyParam

Abs[RJ[30*^-6]]
Abs[RJ[100*^-6]]
Abs[RJ[300*^-6]]
Abs[RJ[1000*^-6]]

893.949

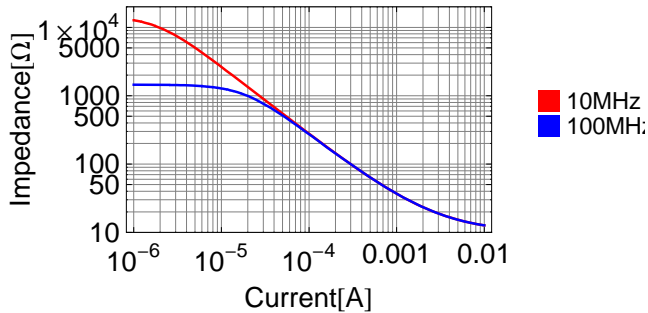
268.215

89.4078

26.8226

```

```
ShowLegend[LogLogPlot[{Abs[ZShottky[i, 10*^6]], Abs[ZShottky[i, 100*^6]]},
  {i, 1*^-6, 1*^-2}, FrameLabel -> {"Current[A]", "Impedance[Ω]"},
  PlotRange -> {10, 2*^4}, Frame -> True, GridLines -> Automatic, PlotStyle ->
  {{Thickness [0.007], Red}, {Thickness [0.007], Blue}, {Thickness [0.007], Black}},
  BaseStyle -> $TextStyle, ImageSize -> Scaled[0.65]],
  {{Graphics[{Red, Rectangle[{1, 1}]}], "10MHz"},
  {Graphics[{Blue, Rectangle[{1, 1}]}], "100MHz"}},
  BaseStyle -> {FontFamily -> "Helvetica", FontSize -> 11}, LegendPosition -> {0.9, -0.0},
  LegendSize -> {0.4, 0.2}, LegendTextSpace -> 3, LegendShadow -> None] // Quiet
```



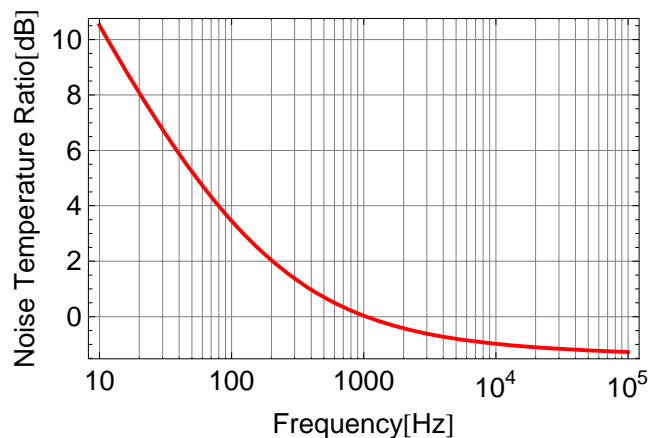
■ Noise Temperature Ratio

```
ShottkyNTRLevel[f_] := 10-1.5/20.
```

```
ShottkyNTRFlicker[f_] :=  $\sqrt{\frac{0.8*^2}{f} + \frac{1}{3} \sqrt[10]{\frac{1*^2}{f}}}$  (* fudge a little bit *)
```

```
ShottkyNTR[f_] :=  $\sqrt{\text{ShottkyNTRLevel}[f]^2 + \text{ShottkyNTRFlicker}[f]^2}$ 
```

```
LogLinearPlot[db[ShottkyNTR[f]], {f, 10, 100 000},
  FrameLabel -> {"Frequency[Hz]", "Noise Temperature Ratio[dB]"}, PlotRange -> All, Frame -> True,
  GridLines -> Automatic, PlotStyle -> {Thickness [0.007], Red}, BaseStyle -> $TextStyle]
```



■ Detection chain

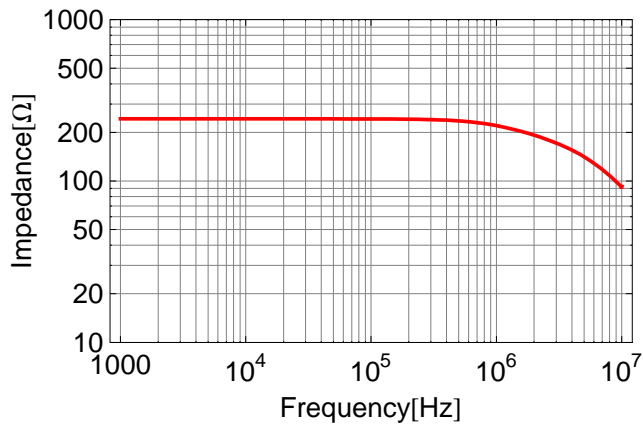
```

detParam = {Rbias → 100*^3, ibias → 240*^-6, Cclamp1 → 330*^-12,
  Cclamp2 → 150*^-12, Cbias → 20*^-6, Rdrv → 2000, Rterm → 50, TransformerRatio → 2};

zdet = par[Rbias,  $\frac{1}{s Cclamp2}$ , ser[ZShottky[ibias, f],
  par[ZShottky[ibias, f], ser[TransformerRatio^2 Rterm,  $\frac{1}{s Cclamp1}$ ]]]]];

LogLogPlot[Abs[zdet] /. detParam /. s → 2 π i f,
  {f, 1*^3, 1*^7}, FrameLabel → {"Frequency[Hz]", "Impedance[Ω]"},
  PlotRange → {10, 1000}, Frame → True, GridLines → Automatic,
  PlotStyle → {{Thickness [0.007], Red}, {Thickness [0.007], Blue}, {Thickness [0.007], Black}},
  BaseStyle → $TextStyle]

```



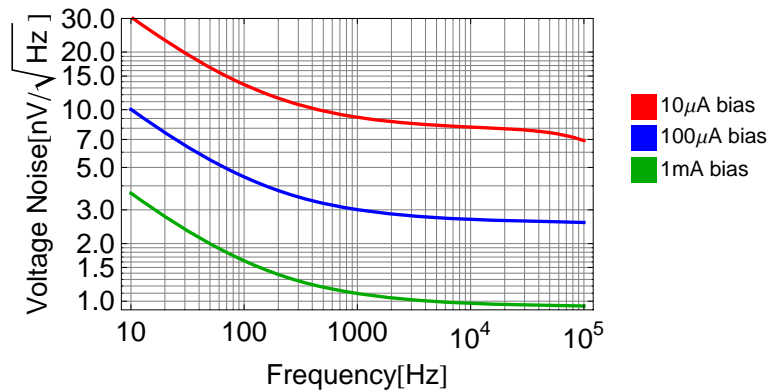
Only valid when the resistance of the bias resistor is larger than the diode junction resistance because the flicker noise is applied to the parallel arrangement as a whole.

```

diodenoise[0] = ShottkyNTR[f]  $\sqrt{\text{FourKT Abs[zdet]}$  /. detParam;
diodenoisebias[0, ib_] :=
  ShottkyNTR[f]  $\sqrt{\text{FourKT Abs[zdet]}$  /. {ibias → ib} /. detParam /. s → 2 π i f;

```

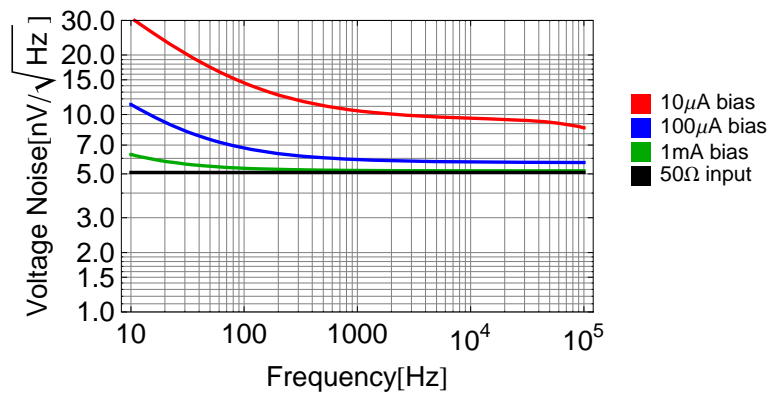
```
ShowLegend[LogLogPlot[{1*^9 Abs[diodenoisebias[0, 1*^-5]],
  1*^9 Abs[diodenoisebias[0, 1*^-4]], 1*^9 Abs[diodenoisebias[0, 1*^-3]]},
{f, 10, 1*^5}, FrameLabel -> {"Frequency[Hz]", "Voltage Noise[nV/√Hz]"},
Frame -> True, PlotRange -> {0.9, 30}, GridLines -> Automatic, PlotStyle ->
{{Thickness[0.007], Red}, {Thickness[0.007], Blue}, {Thickness[0.007], Darker[Green]}},
BaseStyle -> $TextStyle, ImageSize -> Scaled[0.8]},
{{Graphics[{Red, Rectangle[{1, 1}]}], "10μA bias"}, {Graphics[{Blue, Rectangle[{1, 1}]}],
"100μA bias"}, {Graphics[{Darker[Green], Rectangle[{1, 1}]}], "1mA bias"}},
BaseStyle -> {FontFamily -> "Helvetica", FontSize -> 10}, LegendPosition -> {0.85, -0.0},
LegendSize -> {0.5, 0.3}, LegendTextSpace -> 5, LegendShadow -> None}] // Quiet
```



Noise of the 50Ω termination resistor is added twice because we fold the two audio sidebands of the carrier on top of each other. They also have a gain of $2 \times$ transformer ratio.

```
detnoise[0] = √[diodenoise[0]^2 + 2 (2 TransformerRatio)^2 FourKT Rterm] /. detParam;
detnoisebias[0, ib_] =
√[diodenoisebias[0, ib]^2 + 2 (2 TransformerRatio)^2 FourKT Rterm] /. {ibias -> ib} /. detParam /.
s -> 2 π i f;
```

```
ShowLegend[LogLogPlot[{1*^9 Abs[detnoisebias[0, 1*^-5]], 1*^9 Abs[detnoisebias[0, 1*^-4]],
  1*^9 Abs[detnoisebias[0, 1*^-3]], 1*^9  $\sqrt{2 (2 \text{ TransformerRatio})^2 \text{ FourKT } 50 / . \text{ detParam}}$ },
{f, 10, 1*^5}, FrameLabel -> {"Frequency[Hz]", "Voltage Noise[nV/ $\sqrt{\text{Hz}}$ "]},
Frame -> True, PlotRange -> {1, 30}, GridLines -> Automatic, PlotStyle ->
{{Thickness [0.007], Red}, {Thickness [0.007], Blue}, {Thickness [0.007], Darker[Green]},
{Thickness [0.007], Black}}, BaseStyle -> $TextStyle, ImageSize -> Scaled[0.8]},
{{Graphics[{Red, Rectangle[{1, 1}]}], "10 $\mu$ A bias"}, {Graphics[{Blue, Rectangle[{1, 1}]}],
"100 $\mu$ A bias"}, {Graphics[{Darker[Green], Rectangle[{1, 1}]}], "1mA bias"},
{Graphics[{Black, Rectangle[{1, 1}]}], "50 $\Omega$  input"}],
BaseStyle -> {FontFamily -> "Helvetica", FontSize -> 10}, LegendPosition -> {0.85, -0.0},
LegendSize -> {0.5, 0.3}, LegendTextSpace -> 5, LegendShadow -> None}] // Quiet
```



■ Bias chain

Resistor and Shottky noise in bias chain:

$$z_{\text{bias}} = \text{par} \left[R_{\text{bias}}, \frac{1}{s C_{\text{bias}}}, \text{ser} [Z_{\text{Shottky}}[i_{\text{bias}}, f], Z_{\text{Shottky}}[i_{\text{bias}}, f], R_{\text{drv}}] \right];$$

$$\text{NTRratio} = 1 + (\text{ShottkyNTR}[f] - 1) \text{Abs} \left[\frac{\text{ser} [Z_{\text{Shottky}}[i_{\text{bias}}, f], Z_{\text{Shottky}}[i_{\text{bias}}, f]]}{R_{\text{drv}}} \right];$$

$$\text{diodennoise}[1] = \text{NTRratio} \sqrt{\text{FourKT Abs}[z_{\text{bias}}]} /. \text{detParam} /. s \rightarrow 2 \pi i f;$$

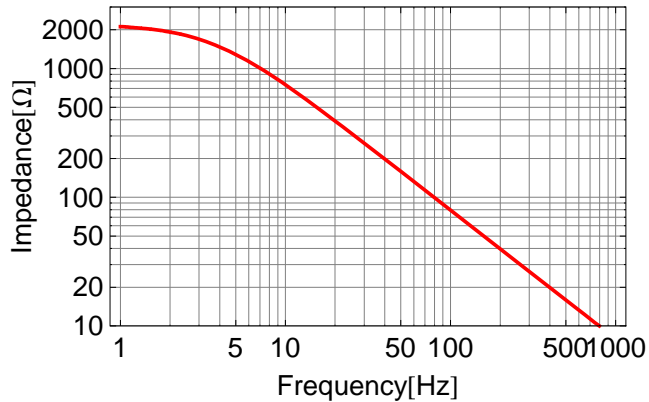
$$\text{diodennoisebias}[1, i_{\text{b}}] :=$$

$$\text{NTRratio} \sqrt{\text{FourKT Abs}[z_{\text{bias}}]} /. \{i_{\text{bias}} \rightarrow i_{\text{b}}\} /. \text{detParam} /. s \rightarrow 2 \pi i f;$$

```

LogLogPlot[Abs[zbias] /. detParam /. s -> 2 π i f,
  {f, 1*^0, 1*^3}, FrameLabel -> {"Frequency[Hz]", "Impedance[Ω]"},
  PlotRange -> {10, 3000}, Frame -> True, GridLines -> Automatic,
  PlotStyle -> {{Thickness [0.007], Red}, {Thickness [0.007], Blue}, {Thickness [0.007], Black}},
  BaseStyle -> $TextStyle]

```



Bias driver and supply noise:

Assume $<100 \frac{\text{nV}}{\sqrt{\text{Hz}}}$ noise on the BIAS drive at $f > 10\text{Hz}$.

Assume $<200 \frac{\text{nV}}{\sqrt{\text{Hz}}}$ noise on the 24V supply side at $f > 10\text{Hz}$.

```
zDrv = 10 000;
```

```
cDrv = 20*^-6;
```

```
driveNoise[0] = 100*^-9;
```

```
supplyNoise[0] = 200*^-9;
```

$$\text{splyDrv}[0] = \frac{\text{par}\left[2 \text{ZShottky}[\text{ibias}, f] + \text{Rdrv}, \frac{1}{s \text{Cbias}}\right]}{\text{par}\left[2 \text{ZShottky}[\text{ibias}, f] + \text{Rdrv}, \frac{1}{s \text{Cbias}}\right] + \text{Rbias}};$$

```
splyNoise[0, ib_] := Abs[splyDrv[0]] supplyNoise[0] /. {ibias -> ib} /. detParam /. s -> 2 π i f;
```

```
splyNoise[0] = splyNoise[0, ibias] /. detParam /. s -> 2 π i f;
```

```

biasDrv[0, ib_] = 
$$\frac{\text{par}\left[\text{Rbias}, \frac{1}{s \text{Cbias}}\right]}{\text{par}\left[\text{Rbias}, \frac{1}{s \text{Cbias}}\right] + 2 \text{ZShottky}[\text{ibias}, f] + \text{Rdrv}}$$
 /. {ibias → ib};
biasDrv[0] = biasDrv[0, ibias];
OpAmpDrv[0, ib_] =
  biasDrv[0] OpAmp[-1, zDrv, par[zDrv,  $\frac{1}{s \text{cDrv}}$ ]] /. {ibias → ib} /. detParam /. s → 2 π i f;
OpAmpDrv[0] = OpAmpDrv[0, ibias] /. detParam /. s → 2 π i f;
OpAmpDrv[1] = OpAmp[-1, zDrv, par[zDrv,  $\frac{1}{s \text{cDrv}}$ ]] /. s → 2 π i f;
OpAmpDrv[2] = OpAmp[1, ∞, 1]; OpAmpNoiseDrv[1, ib_] =
  OpAmpNoise[-1, zDrv, par[zDrv,  $\frac{1}{s \text{cDrv}}$ ], en, in] /. {ibias → ib} /. detParam /. s → 2 π i f /.
  OP27[f];
OpAmpNoiseDrv[1] = OpAmpNoiseDrv[1, ibias] /. detParam /. s → 2 π i f;
OpAmpNoiseDrv[2, ib_] =
  
$$\sqrt{\left(\text{OpAmpNoise}[1, \infty, 0, \text{en}, \text{in}]^2 + \text{in}^2 \text{Abs}\left[\text{par}\left[z\text{Drv}, \frac{1}{s \text{cDrv}}\right]\right]^2 + \text{FourKT} \text{Abs}\left[\text{par}\left[z\text{Drv}, \frac{1}{s \text{cDrv}}\right]\right]\right)} /.
  \{ibias \rightarrow ib\} /. \text{detParam} /. s \rightarrow 2 \pi i f /. \text{OP27}[f];
OpAmpNoiseDrv[2] = OpAmpNoiseDrv[2, ibias] /. detParam /. s → 2 π i f;
(* averaged output noise through bias network*)
OpAmpNoiseDrv[0, ib_] = Abs[biasDrv[0, ib]]
  
$$\sqrt{\left(\frac{1}{2} \left(\text{Abs}[\text{OpAmpDrv}[1]]^2 \text{OpAmpNoiseDrv}[1, ib]^2 + \text{Abs}[\text{OpAmpDrv}[2]]^2 \text{OpAmpNoiseDrv}[2, ib]^2\right)\right)};
OpAmpNoiseDrv[0] = OpAmpNoiseDrv[0, ibias] /. detParam /. s → 2 π i f;
drvNoise[0, ib_] = driveNoise[0] Abs[OpAmpDrv[0, ib]];
drvNoise[0] = driveNoise[0] Abs[OpAmpDrv[0]];$$$$

```

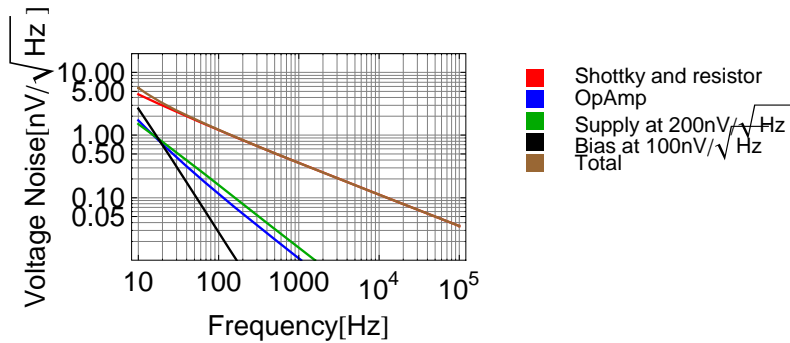
Total noise is bias chain:

```

detnoise[1] = 
$$\sqrt{\text{diodeNoise}[1]^2 + \text{OpAmpNoiseDrv}[0]^2 + \text{splyNoise}[0]^2 + \text{drvNoise}[0]^2};
detnoisebias[1, ib_] =
  
$$\sqrt{\left(\text{diodeNoiseBias}[1, ib]^2 + \text{OpAmpNoiseDrv}[0, ib]^2 + \text{splyNoise}[0, ib]^2 + \text{drvNoise}[0, ib]^2\right)} /.
  \{ibias \rightarrow ib\} /. \text{detParam} /. s \rightarrow 2 \pi i f;$$$$

```

```
ShowLegend[LogLogPlot[{1*^9 diodenoise[1],
  1*^9 OpAmpNoiseDrv[0], 1*^9 splyNoise[0], 1*^9 drvNoise[0], 1*^9 detnoise[1]},
{f, 10, 100 000}, FrameLabel -> {"Frequency[Hz]", "Voltage Noise[nV/√Hz]"},
Frame -> True, PlotRange -> {0.01, 20}, GridLines -> Automatic, PlotStyle ->
{{Thickness [0.007], Red}, {Thickness [0.007], Blue}, {Thickness [0.007], Darker[Green]},
{Thickness [0.007], Black}, {Thickness [0.007], Brown}}, BaseStyle -> $TextStyle,
ImageSize -> Scaled[0.8]}, {{Graphics[{Red, Rectangle[{1, 1}]}], "Shottky and resistor"},
{Graphics[{Blue, Rectangle[{1, 1}]}], "OpAmp"},
{Graphics[{Darker[Green], Rectangle[{1, 1}]}], "Supply at 200nV/√Hz"},
{Graphics[{Black, Rectangle[{1, 1}]}], "Bias at 100nV/√Hz"},
{Graphics[{Brown, Rectangle[{1, 1}]}], "Total"}},
BaseStyle -> {FontFamily -> "Helvetica", FontSize -> 10}, LegendPosition -> {0.87, -0.0},
LegendSize -> {1, 0.4}, LegendTextSpace -> 5, LegendShadow -> None}] // Quiet
```



Bias chain transfer function

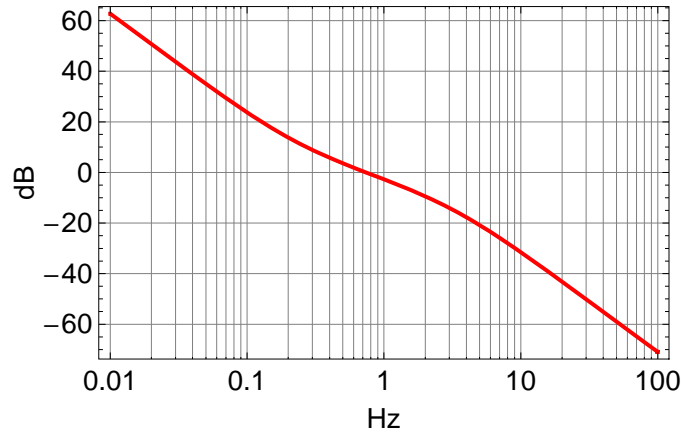
$$\text{comp}[f_] := \frac{i f + 0.7}{i f} \frac{i f + 0.2}{i f}$$

dB[OpAmpDrv[0]] /. f -> 1

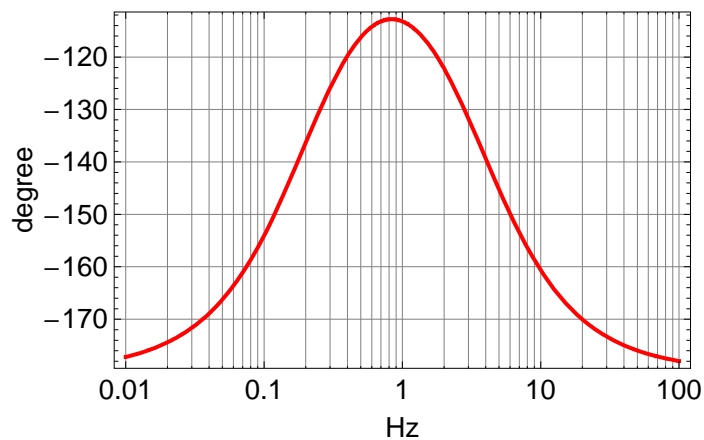
-4.62572

```
BodePlot[OpAmpDrv[0] comp[f], {f, 0.01, 100}, PlotStyle ->
  {{Thickness [0.007], Red}, {Thickness [0.007], Blue}, {Thickness [0.007], Darker[Green]},
  {Thickness [0.007], Black}, {Thickness [0.007], Brown}}, BaseStyle -> $TextStyle]
```

Magnitude



Phase

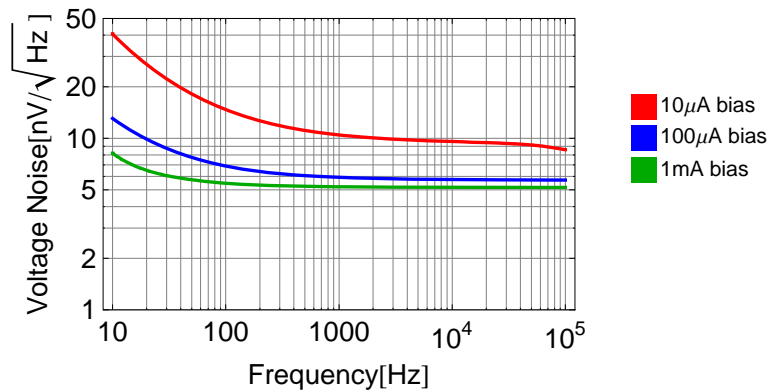


■ Sum of Detector and Bias chain

$$\text{detnoise}[3] = \sqrt{\text{detnoise}[0]^2 + \text{detnoise}[1]^2} ;$$

$$\text{detnoisebias}[3, \text{ib}_] = \sqrt{\text{detnoisebias}[0, \text{ib}]^2 + \text{detnoisebias}[1, \text{ib}]^2} ;$$

```
ShowLegend[LogLogPlot[{1*^9 Abs[detnoisebias[3, 1*^-5]],
  1*^9 Abs[detnoisebias[3, 1*^-4]], 1*^9 Abs[detnoisebias[3, 1*^-3]]},
{f, 10, 1*^5}, FrameLabel -> {"Frequency[Hz]", "Voltage Noise[nV/√Hz]"},
Frame -> True, PlotRange -> {1, 50}, GridLines -> Automatic, PlotStyle ->
{{Thickness[0.007], Red}, {Thickness[0.007], Blue}, {Thickness[0.007], Darker[Green]}},
BaseStyle -> $TextStyle, ImageSize -> Scaled[0.8]},
{{Graphics[{Red, Rectangle[{1, 1}]}], "10μA bias"}, {Graphics[{Blue, Rectangle[{1, 1}]}],
"100μA bias"}, {Graphics[{Darker[Green], Rectangle[{1, 1}]}], "1mA bias"}},
BaseStyle -> {FontFamily -> "Helvetica", FontSize -> 10}, LegendPosition -> {0.85, -0.0},
LegendSize -> {0.5, 0.3}, LegendTextSpace -> 5, LegendShadow -> None}] // Quiet
```



Instrumentation Amp

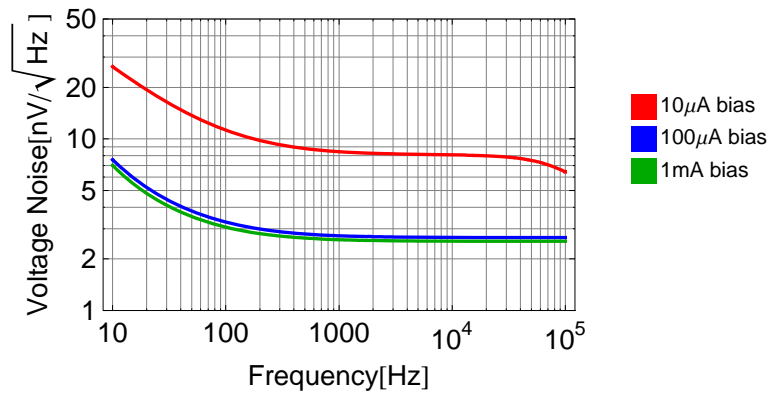
```
z1[1] = par[1000,  $\frac{1}{s \cdot 150 \cdot 10^{-12}}$ ];
z2[1] = 110; (* half middle resistor *)
opamp[1] = 1 +  $\frac{z1[1]}{z2[1]}$  /. s -> 2 π i f; (* differential gain *)
opampnoise[1, ib_] =

$$\sqrt{\left( 2 \text{en}^2 + (\text{in Abs}[zdet])^2 + (\text{in Abs}[zbias])^2 + 2 (\text{in Abs}[\text{par}[z1[1], z2[1]]])^2 + 2 \text{FourKT Abs}[\text{par}[z1[1], z2[1]]] \text{Abs}\left[\frac{1}{1 + \frac{z1[1]}{2 z2[1]}}\right] \right) /. \{ibias \rightarrow ib\} /. \text{detParam} /. s \rightarrow 2 \pi i f /. \text{AD829}[f];$$

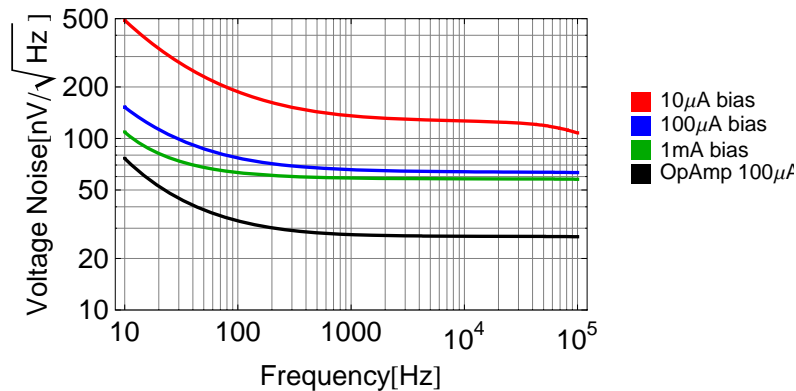
opampnoise[1] = opampnoise[1, ibias] /. detParam /. s -> 2 π i f;
totalnoise[1, ib_] = Abs[opamp[1]]  $\sqrt{\text{opampnoise}[1, ib]^2 + \text{detnoisebias}[3, ib]^2} /. s \rightarrow 2 \pi i f;$ 
totalnoise[1] = totalnoise[1, ibias] /. detParam /. s -> 2 π i f;
totalnoise[1, 1*^-4] /. f -> 1000
Abs[opamp[1]] opampnoise[1, 1*^-4] /. f -> 1000
6.58145 × 10-8
2.75513 × 10-8
```

The noise of the OpAmp is dominated by the current noise through the source impedance for bias currents smaller than 100μA.


```
ShowLegend[
  LogLogPlot[{1*^9 opampnoise[1, 1*^-5], 1*^9 opampnoise[1, 1*^-4], 1*^9 opampnoise[1, 1*^-3]},
    {f, 10, 1*^5}, FrameLabel -> {"Frequency[Hz]", "Voltage Noise[nV/√Hz]"},
    Frame -> True, PlotRange -> {1, 50}, GridLines -> Automatic, PlotStyle ->
      {{Thickness[0.007], Red}, {Thickness[0.007], Blue}, {Thickness[0.007], Darker[Green]}},
      {Thickness[0.007], Black}}, BaseStyle -> $TextStyle, ImageSize -> Scaled[0.8]],
  {{{Graphics[{Red, Rectangle[{1, 1}]}], "10μA bias"}, {Graphics[{Blue, Rectangle[{1, 1}]}],
    "100μA bias"}, {Graphics[{Darker[Green], Rectangle[{1, 1}]}], "1mA bias"}},
  BaseStyle -> {FontFamily -> "Helvetica", FontSize -> 10}, LegendPosition -> {0.85, -0.0},
  LegendSize -> {0.5, 0.3}, LegendTextSpace -> 5, LegendShadow -> None}] // Quiet
```



```
ShowLegend[LogLogPlot[{1*^9 totalnoise[1, 1*^-5], 1*^9 totalnoise[1, 1*^-4],
  1*^9 totalnoise[1, 1*^-3], 1*^9 Abs[opamp[1]] opampnoise[1, 1*^-4]},
{f, 10, 1*^5}, FrameLabel -> {"Frequency[Hz]", "Voltage Noise[nV/√Hz]"},
Frame -> True, PlotRange -> {10, 500}, GridLines -> Automatic, PlotStyle ->
{{Thickness[0.007], Red}, {Thickness[0.007], Blue}, {Thickness[0.007], Darker[Green]},
{Thickness[0.007], Black}}, BaseStyle -> $TextStyle, ImageSize -> Scaled[0.8]},
{{Graphics[{Red, Rectangle[{1, 1}]}], "10μA bias"}, {Graphics[{Blue, Rectangle[{1, 1}]}],
"100μA bias"}, {Graphics[{Darker[Green], Rectangle[{1, 1}]}], "1mA bias"},
{Graphics[{Black, Rectangle[{1, 1}]}], "OpAmp 100μA bias"}},
BaseStyle -> {FontFamily -> "Helvetica", FontSize -> 10}, LegendPosition -> {0.85, -0.0},
LegendSize -> {0.5, 0.3}, LegendTextSpace -> 5, LegendShadow -> None] // Quiet
```



Differential Amp

The 50Ω termination noise is correlated between the two detector chains it has to be added coherently, whereas the shottky noise does not.

$$z1[2] = \frac{3300}{2};$$

$$z2[2] = \text{par}\left[3300, \frac{1}{s \cdot 68 \cdot 10^{-12}}\right];$$

$$\text{opamp}[2] = \text{OpAmp}[0, z1[2], z2[2]] /. s \rightarrow 2 \pi i f; (* gain *)$$

$$\text{opampnoise}[2] = \text{OpAmpNoise}[0, z1[2], z2[2], \text{en}, \text{in}] /. s \rightarrow 2 \pi i f /. \text{AD829}[f];$$

$$\text{corrnoise} = \text{Abs}[\text{opamp}[1]] \sqrt{(2 \text{TransformerRatio})^2 \text{FourKTRterm}} /. \text{detParam};$$

$$\text{totalnoise}[2, \text{ib}_] =$$

$$\text{Abs}[\text{opamp}[2]] \sqrt{\text{opampnoise}[2]^2 + \frac{\text{totalnoise}[1, \text{ib}]^2 + \text{corrnoise}^2}{2}} /. s \rightarrow 2 \pi i f;$$

$$\text{totalnoise}[2] = \text{totalnoise}[2, \text{ibias}] /. \text{detParam} /. s \rightarrow 2 \pi i f;$$

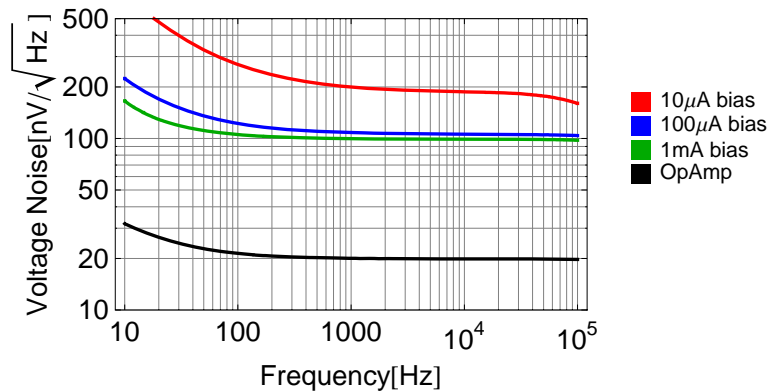
$$\text{totalnoise}[2, 1*^-4] /. f \rightarrow 1000$$

$$\text{Abs}[\text{opamp}[2]] \text{opampnoise}[2] /. f \rightarrow 1000$$

$$1.08187 \times 10^{-7}$$

$$2.00493 \times 10^{-8}$$

```
ShowLegend[LogLogPlot[{1*^9 totalnoise[2, 1*^-5], 1*^9 totalnoise[2, 1*^-4],
  1*^9 totalnoise[2, 1*^-3], 1*^9 Abs[opamp[2]] opampnoise[2]},
  {f, 10, 1*^5}, FrameLabel -> {"Frequency[Hz]", "Voltage Noise[nV/√Hz]"},
  Frame -> True, PlotRange -> {10, 500}, GridLines -> Automatic, PlotStyle ->
  {{Thickness[0.007], Red}, {Thickness[0.007], Blue}, {Thickness[0.007], Darker[Green]},
  {Thickness[0.007], Black}}, BaseStyle -> $TextStyle, ImageSize -> Scaled[0.8]},
  {{Graphics[{Red, Rectangle[{1, 1}]}], "10μA bias"}, {Graphics[{Blue, Rectangle[{1, 1}]}],
  "100μA bias"}, {Graphics[{Darker[Green], Rectangle[{1, 1}]}], "1mA bias"},
  {Graphics[{Black, Rectangle[{1, 1}]}], "OpAmp"}},
  BaseStyle -> {FontFamily -> "Helvetica", FontSize -> 10}, LegendPosition -> {0.85, -0.0},
  LegendSize -> {0.5, 0.3}, LegendTextSpace -> 5, LegendShadow -> None] // Quiet
```



Input Referred Noise

$$\text{carrier} = \frac{1}{\sqrt{2}}; (* 10 \text{ dBm} *)$$

$$\text{loss} = \text{FromdB}[-1.];$$

$$\text{detectorgain} = 2 \text{ Abs[opamp[1] opamp[2] /. f -> 0] TransformerRatio loss /. detParam}$$

$$\text{carriernoise}[ib_] := \frac{\text{totalnoise}[2, ib]}{\text{detectorgain carrier}}$$

$$\text{FiftyOhm} = \frac{\sqrt{2 \text{ FourKT } 50}}{\text{carrier}};$$

$$\text{noisefigure}[ib_] := \frac{\text{carriernoise}[ib]}{\text{FiftyOhm}}$$

$$\text{dB}[\text{carriernoise}[1*^-4] /. f -> 1000]$$

$$\text{dB}[\text{FiftyOhm}]$$

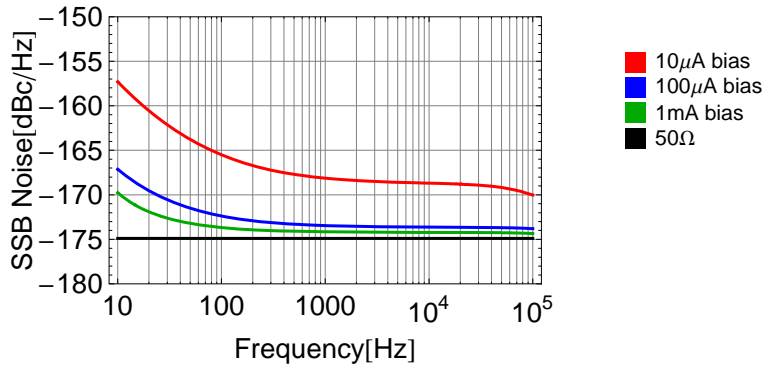
71.9483

-173.447

-174.895

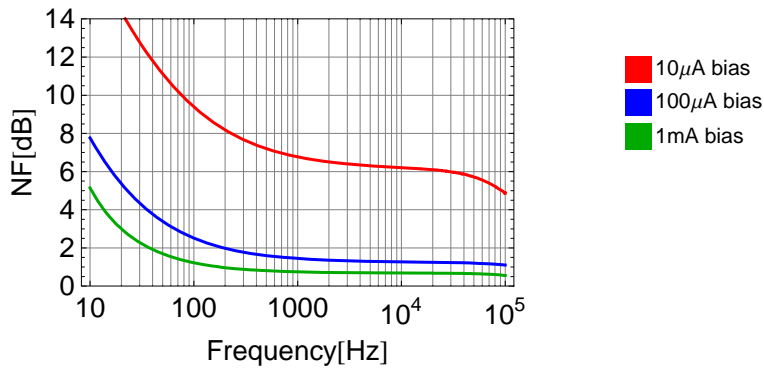
```
ShowLegend[LogLinearPlot[{dB[carriernoise[1*^-5]],
  dB[carriernoise[1*^-4]], dB[carriernoise[1*^-3]], dB[ $\sqrt{2 \text{ FourKT } 50} / \text{carrier}$ ]},
  {f, 10, 1*^5}, FrameLabel -> {"Frequency[Hz]", "SSB Noise[dBc/Hz]},
  PlotLabel -> "Input Referred Noise / 10dBm signal", Frame -> True, PlotRange -> {-180, -150},
  GridLines -> Automatic, PlotStyle -> {{Thickness [0.007], Red}, {Thickness [0.007], Blue},
  {Thickness [0.007], Darker[Green]}, {Thickness [0.007], Black}}, BaseStyle -> $TextStyle,
  ImageSize -> Scaled[0.8]}, {{Graphics[{Red, Rectangle[{1, 1}]}], "10 $\mu$ A bias"},
  {Graphics[{Blue, Rectangle[{1, 1}]}], "100 $\mu$ A bias"},
  {Graphics[{Darker[Green], Rectangle[{1, 1}]}], "1mA bias"},
  {Graphics[{Black, Rectangle[{1, 1}]}], "50 $\Omega$ "},
  BaseStyle -> {FontFamily -> "Helvetica", FontSize -> 10}, LegendPosition -> {0.75, -0.0},
  LegendSize -> {0.5, 0.3}, LegendTextSpace -> 5, LegendShadow -> None}] // Quiet
```

Input Referred Noise / 10dBm signal



```
ShowLegend[
LogLinearPlot[{dB[noisefigure[1*^-5]], dB[noisefigure[1*^-4]], dB[noisefigure[1*^-3]]},
{f, 10, 1*^5}, FrameLabel -> {"Frequency[Hz]", "NF[dB]"}, PlotLabel -> "Noise Figure",
Frame -> True, PlotRange -> {0, 14}, GridLines -> Automatic, PlotStyle ->
{{Thickness [0.007], Red}, {Thickness [0.007], Blue}, {Thickness [0.007], Darker[Green]}},
{Thickness [0.007], Black}}, BaseStyle -> $TextStyle, ImageSize -> Scaled[0.8]],
{{{Graphics[{Red, Rectangle[{1, 1}]}], "10μA bias"}, {Graphics[{Blue, Rectangle[{1, 1}]}],
"100μA bias"}, {Graphics[{Darker[Green], Rectangle[{1, 1}]}], "1mA bias"}},
BaseStyle -> {FontFamily -> "Helvetica", FontSize -> 10}, LegendPosition -> {0.75, -0.0},
LegendSize -> {0.5, 0.3}, LegendTextSpace -> 5, LegendShadow -> None} // Quiet
```

Noise Figure



Bias Servo Compensation Network

```
prn = {fknee → 0.7, R2 → 10 000, R1 → 20 000, C → 20*^-6}
```

```
op1 = OpAmp[-1, R1,  $\frac{1}{s C} + R2$ ] // Simplify
```

```
Solve[op1 ==  $\frac{R2 s + 2 \pi \text{fknee}}{R1 s}$ , C][[1]]
```

```
1*^6 C /. % /. prn
```

```
LogLogPlot[1*^9 OpAmpNoise[-1, R1,  $\frac{1}{s C} + R2$ , en, in] /. OP27[f] /. prn, {f, 1, 1*^5},
```

```
FrameLabel → {"Frequency[Hz]", "Voltage Noise[nV/√Hz]"}, Frame → True, PlotRange → {1, 1000},
```

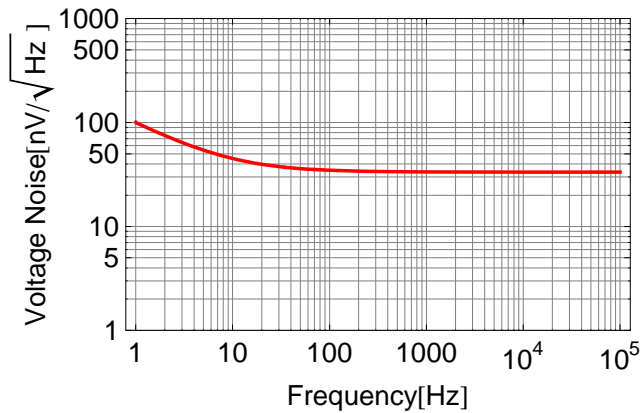
```
GridLines → Automatic, PlotStyle → {Thickness [0.007], Red}, BaseStyle → $TextStyle]
```

```
{fknee → 0.7, R2 → 10 000, R1 → 20 000, C →  $\frac{1}{50 000}$ }
```

$$\frac{R2 + \frac{1}{C s}}{R1}$$

```
{C →  $\frac{1}{2 \text{fknee} \pi R2}$ }
```

```
22.7364
```



```
Abs[op1] /. s → 2 π i 1. /. prn
```

```
10 $\frac{-4.63}{20}$ 
```

```
gain = 20 % %%
```

```
0.638995
```

```
0.586813
```

```
7.49941
```

```

prm2 = {fknee → 0.2, R2 →  $\frac{1}{2 \pi \text{fknee } C}$ , C → 20*^-6}
prm3 = {fknee → 0.2, R1 → 300 000, R2 → 40 000, C → 20*^-6}
R2 /. prm2

op2 = OpAmp[-1, R1,  $\frac{1}{s C} + R2$ ] // Simplify

fr = FindRoot[ $\left( \text{Abs}[op2] == \frac{1}{\text{gain}} \text{ /. prm2 / . s} \rightarrow 2 \pi i 1 \right)$ , {R1, 1000}]

LogLogPlot[1*^9 OpAmpNoise[-1, R1,  $\frac{1}{s C} + R2$ , en, in] /. LT1012[f] /. prm2 /. fr, {f, 1, 1*^5},
  FrameLabel → {"Frequency[Hz]", "Voltage Noise[nV/√Hz]"}, Frame → True, PlotRange → {1, 1000},
  GridLines → Automatic, PlotStyle → {Thickness [0.007], Red}, BaseStyle → $TextStyle]

{fknee → 0.2, R2 →  $\frac{1}{2 C \text{fknee } \pi}$ , C →  $\frac{1}{50 000}$ }

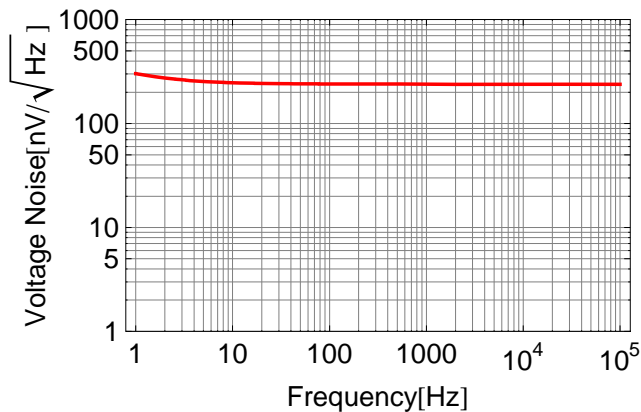
{fknee → 0.2, R1 → 300 000, R2 → 40 000, C →  $\frac{1}{50 000}$ }

39 788.7

 $\frac{R2 + \frac{1}{C s}}{R1}$ 

{R1 → 304 302.}

```



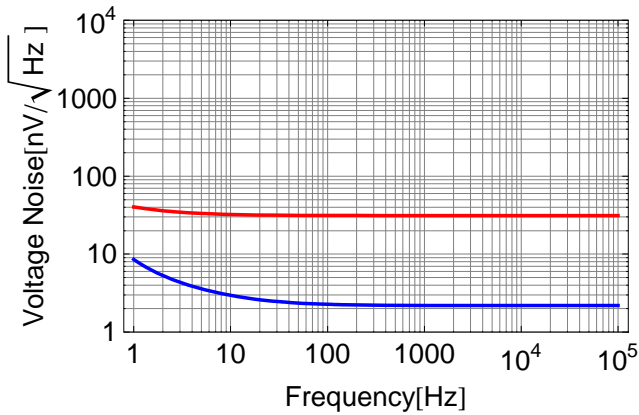
```

Abs[op1] /. s → 2 π i 1. /. prm2 /. fr

0.133344

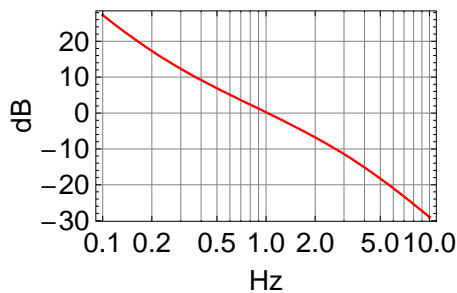
```

```
LogLogPlot[{{1*^9 Abs[op2] OpAmpNoise[-1, R1,  $\frac{1}{s C} + R2$ , en, in] /. LT1012[f] /. prm2 /. fr,
(Abs[op2] /. prm2 /. fr) 1*^9 Abs[op1] OpAmpNoise[-1, R1,  $\frac{1}{s C} + R2$ , en, in] /. OP27[f] /. prm},
{f, 1, 1*^5}, FrameLabel -> {"Frequency[Hz]", "Voltage Noise[nV/ $\sqrt{\text{Hz}}$ "]},
Frame -> True, PlotRange -> {1, 10 000}, GridLines -> Automatic,
PlotStyle -> {{Thickness [0.007], Red}, {Thickness [0.007], Blue}}, BaseStyle -> $TextStyle]
```

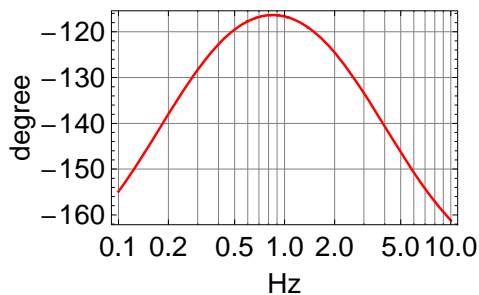


```
t1 = op1 /. prm /. s -> 2 π i f;
t2 = op2 /. prm3 /. fr /. s -> 2 π i f;
BodePlot[20 t1 t2 OpAmpDrv[0], {f, 0.1, 10}, PlotStyle ->
{{Thickness [0.007], Red}, {Thickness [0.007], Blue}, {Thickness [0.007], Darker[Green]},
{Thickness [0.007], Black}, {Thickness [0.007], Brown}}, BaseStyle -> $TextStyle]
```

Magnitude



Phase



Bias Setpoints

```

set = Table[10 $\frac{i}{20 \times 5}$ , {i, 0, 12 * 10 - 1}];
dac = 1 / set * (216 - 1) // Round // Reverse

{4231, 4330, 4431, 4534, 4640, 4748, 4858, 4971, 5087, 5206, 5327, 5451, 5578, 5708, 5841,
 5977, 6116, 6259, 6404, 6554, 6706, 6862, 7022, 7186, 7353, 7524, 7700, 7879, 8063,
 8250, 8443, 8639, 8840, 9046, 9257, 9473, 9693, 9919, 10150, 10387, 10629, 10876,
 11129, 11389, 11654, 11925, 12203, 12487, 12778, 13076, 13381, 13692, 14011, 14337,
 14671, 15013, 15363, 15721, 16087, 16462, 16845, 17237, 17639, 18050, 18470,
 18901, 19341, 19791, 20252, 20724, 21207, 21701, 22206, 22723, 23253, 23794,
 24349, 24916, 25496, 26090, 26698, 27320, 27956, 28607, 29273, 29955, 30653,
 31367, 32098, 32845, 33610, 34393, 35194, 36014, 36853, 37711, 38590, 39489,
 40409, 41350, 42313, 43299, 44307, 45339, 46395, 47476, 48582, 49713, 50871,
 52056, 53269, 54510, 55779, 57079, 58408, 59769, 61161, 62585, 64043, 65535}

```

AM Stabilization Servo Compensation Network

Voltage Controlled Attenuator

$$VCA_{\text{pole}} = \frac{1}{2\pi \cdot 0.2 \cdot 10^{-6}}$$

795775.

```

VCAactuator = {{15, -1.9}, {6, -6}, {5, -9}, {4, -12.1},
  {3, -18}, {2.7, -22.4}, {2.5, -28}, {2.4, -35}, {2.3, -42.5}};

```

```

VCAfit[x_] = Fit[VCAactuator, {1,  $\sqrt[3]{x-2.2}$ ,  $\sqrt[4]{x-2.2}$ ,  $\sqrt[6]{x-2.2}$ ,  $\sqrt[8]{x-2.2}$ }, x]

```

```

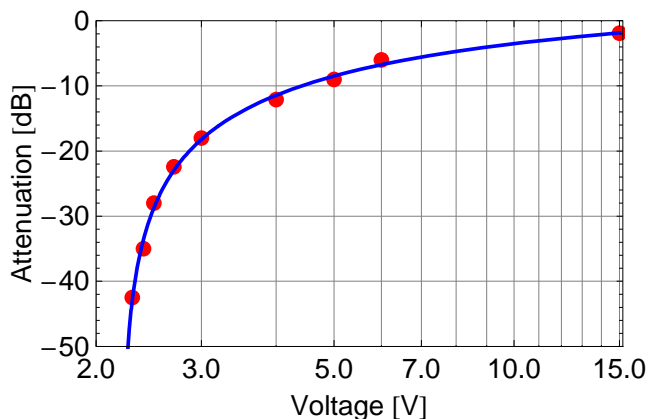
-355.953 + 1352.29 (-2.2 + x)1/8 - 1087.06 (-2.2 + x)1/6 + 65.0966 (-2.2 + x)1/4 + 9.43308  $\sqrt{-2.2 + x}$ 

```

```

Show[ListLogLinearPlot[VCAactuator, PlotStyle -> {Red, PointSize [0.03]},
  Frame -> True, GridLines -> Automatic, PlotRange -> {{2, 15.2}, {-50, 0}},
  FrameLabel -> {"Voltage [V]", "Attenuation [dB]"}, BaseStyle -> $TextStyle],
  LogLinearPlot[VCAfit[x], {x, 1, 15}, PlotRange -> {{0, 15}, All},
  PlotStyle -> {Thickness [0.007], RGBColor [0, 0, 1]}]

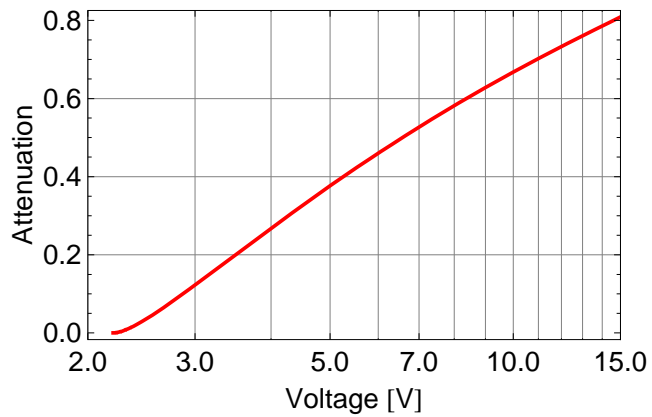
```



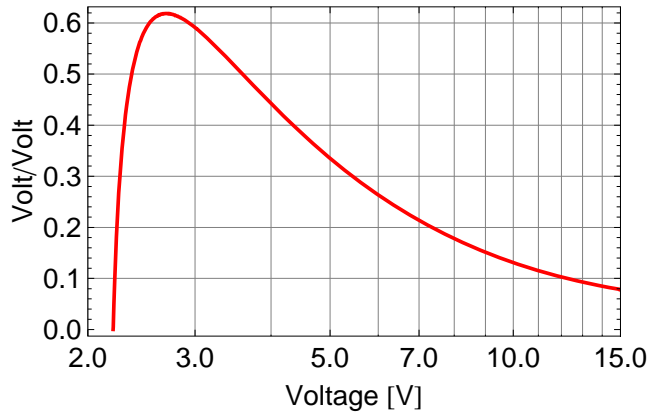
```

wpoint = -8;
wrange = 24;
wabs = 3.55; (* 24dBm *)
wvoltage = x /. FindRoot[VCAfit[x] == wpoint, {x, 5}]
wvoltage2 = x /. FindRoot[VCAfit[x] == wpoint - wrange, {x, 5}]
D[wabs FromdB[VCAfit[x]], x] /. x -> wvoltage
D[wabs FromdB[VCAfit[x]], x] /. x -> wvoltage2
wmax = FindMaximum[D[wabs FromdB[VCAfit[x]], x], {x, 3}]
5.23789
2.42797
0.315633
0.558609
{0.618598, {x -> 2.69043}}
LogLinearPlot[ FromdB[VCAfit[x]], {x, 2, 15}, Frame -> True, GridLines -> Automatic,
PlotRange -> {{2, 15}, All}, PlotStyle -> {Thickness [0.007], Red},
FrameLabel -> {"Voltage [V]", "Attenuation"}, BaseStyle -> $TextStyle]

```



```
LogLinearPlot[D[wabs FromdB[VCAfit[y]], y] /. y -> x, {x, 2, 15}, Frame -> True,
  GridLines -> Automatic, PlotRange -> {{2, 15}, All}, PlotStyle -> {Thickness [0.007], Red},
  FrameLabel -> {"Voltage [V]", "Volt/Volt"}, BaseStyle -> $TextStyle]
```



Detector Transfer Function

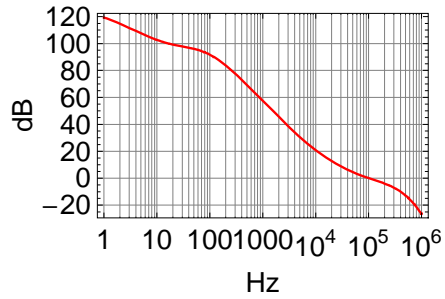
- Data

- Compensation Design

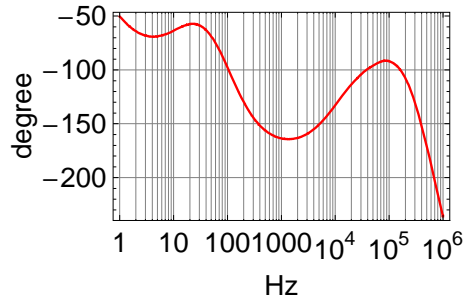
```
comp[f_] :=
  2*^5 pole[f, 100] zero[f, 1*^5] pole[f, 100] zero[f, 1*^4] pole[f, 0.756] zero[f, 15.12]
trans[f_] := comp[f] wmax[1] pole[f, VCApole] dettrans[f]
gainadj =  $\frac{1}{\text{Abs}[trans[1*^5]]}$ 
0.294998
```

```
BodePlot[gainadj trans[f], {f, 1, 1 000 000}, MagnitudeRange -> All,
PhaseRange -> All, PlotStyle -> {Thickness [0.007], Red}, BaseStyle -> $TextStyle]
```

Magnitude

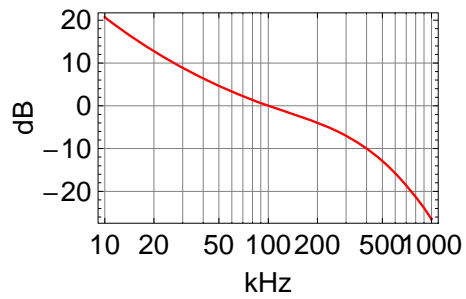


Phase

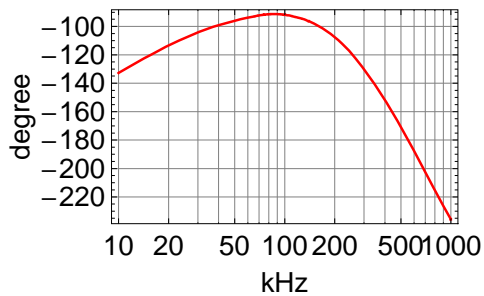


```
BodePlot[gainadj trans[1000 f], {f, 10, 1000}, MagnitudeRange -> All, PhaseRange -> All,
XAxisLabel -> "kHz", PlotStyle -> {Thickness [0.007], Red}, BaseStyle -> $TextStyle]
```

Magnitude



Phase



Compensation Network

This includes a polarity switch, an excitation summing junction, a boost gain, a resistive divider network, the compensation filter, a limiter and an output driver.

■ Polarity Switch

```
z1[1] = 3300;
z2[1] = par[3300,  $\frac{1}{s \cdot 27 \cdot 10^{-12}}$ ];
opamp[1] = OpAmp[-1, z1[1], z2[1]] /. s -> 2 pi i f;
opampnoise[1] = OpAmpNoise[-1, z1[1], z2[1], en, in] /. s -> 2 pi i f /. AD829[f];
```

■ Excitation Summing Junction

```
z1[2] = 3300;
z2[2] = par[3300,  $\frac{1}{s \cdot 10 \cdot 10^{-12}}$ ];
opamp[2] = OpAmp[-1, z1[2], z2[2]] /. s -> 2 pi i f;
opampnoise[2] = OpAmpNoise[-1, z1[2], z2[2], en, in] /. s -> 2 pi i f /. AD829[f];
```

■ Boost Gain

```
z1[3] = 1500;
z2[3] = par[1*10^6,  $\frac{1}{s \cdot 10 \cdot 10^{-9}}$ ];
opamp[3] = OpAmp[1, z1[3], z2[3]] /. s -> 2 pi i f;
opampnoise[3] = OpAmpNoise[1, z1[3], z2[3], en, in] /. s -> 2 pi i f /. AD829[f];
```

■ Resistive Divider Network

```
z1[4] = 3500;
opamp[4] = gainadj;
opampnoise[4] =  $\frac{\sqrt{\text{FourKT Abs}[z1[4]] + \text{in}^2 \text{Abs}[z1[4]]^2}}{2 \text{gainadj}}$  /. s -> 2 pi i f /. AD829[f];
```

■ Compensation Filter

```
z1[5] = 82;
z2[5] =  $\frac{1}{s \cdot 10 \cdot 10^{-9}} + 82$ ;
opamp[5] = OpAmp[1, z1[5], z2[5]] /. s -> 2 pi i f;
opampnoise[5] = OpAmpNoise[1, z1[5], z2[5], en, in] /. s -> 2 pi i f /. AD829[f];
```

■ Limiter

```

z1[6] = ∞;
z2[6] = 100;
opamp[6] = OpAmp[1, z1[6], z2[6]] /. s → 2 π i f;
opampnoise[6] = OpAmpNoise[1, z1[6], z2[6], en, in] /. s → 2 π i f /. AD829[f];

```

■ Output Driver

```

z1[7] = 10 000;
z2[7] = par[10 000, 526 +  $\frac{1}{s 20 \times 10^{-6}}$ ];
opamp[7] = OpAmp[-1, z1[7], z2[7]] /. s → 2 π i f;
opampnoise[7] = OpAmpNoise[-1, z1[7], z2[7], en, in] /. s → 2 π i f /. AD829[f];

```

■ Total

```

stages = 7;
opamp[0] = Simplify[OpAmpProduct[opamp, stages]];
opampnoise[0] = Simplify[OpAmpNoiseProduct[opamp, opampnoise, stages]];

loop[0] = dettrans[f] opamp[0] wmax[[1]] pole[f, VCApole];
loopnoise[0] =  $\sqrt{\text{opampnoise}[0]^2 + \text{totalnoise}[2]^2}$ ;

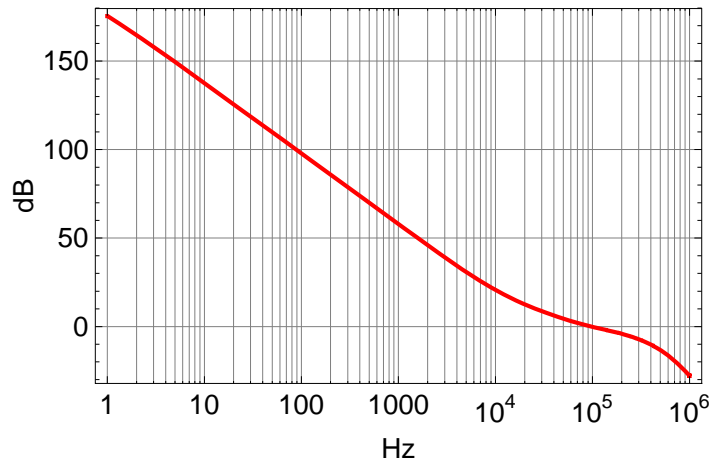
Join[{"Frequency", "Magnitude (dB)", "Phase (°)"}, {}],
{#, dB[loop[0]] /. f → #, Arg[loop[0]] / Degree /. f → #} & /@
{0.01, 0.1, 1, 10, 100, 1000, 1*^4, 1*^5, 1*^6} // TableForm

```

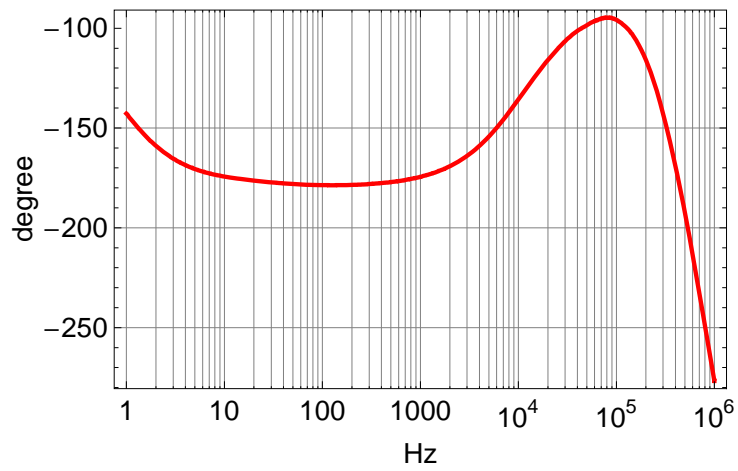
Frequency	Magnitude (dB)	Phase (°)
0.01	219.905	-90.7559
0.1	199.831	-97.5157
1	175.515	-142.718
10	137.581	-174.299
100	97.9065	-178.577
1000	57.9553	-174.435
10 000	20.7162	-135.746
100 000	-0.143135	-95.8403
1 000 000	-27.8508	83.3147

```
BodePlot[loop[0], {f, 1, 1 000 000}, MagnitudeRange → All, PhaseRange → All,  
PhaseReference → -180, PlotStyle → {Thickness [0.007], Red}, BaseStyle → $TextStyle]
```

Magnitude

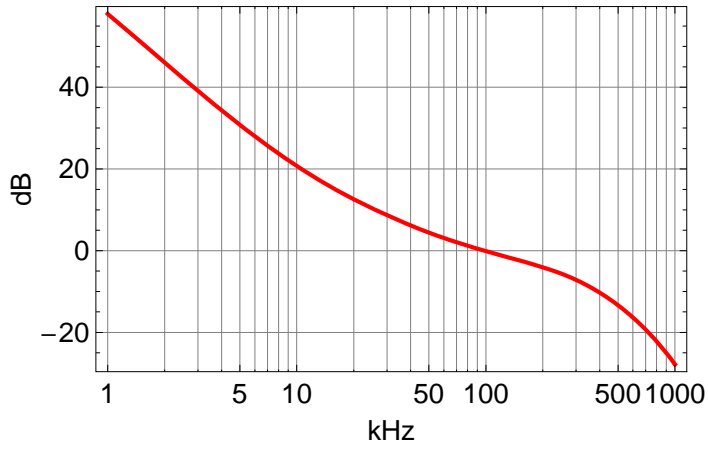


Phase

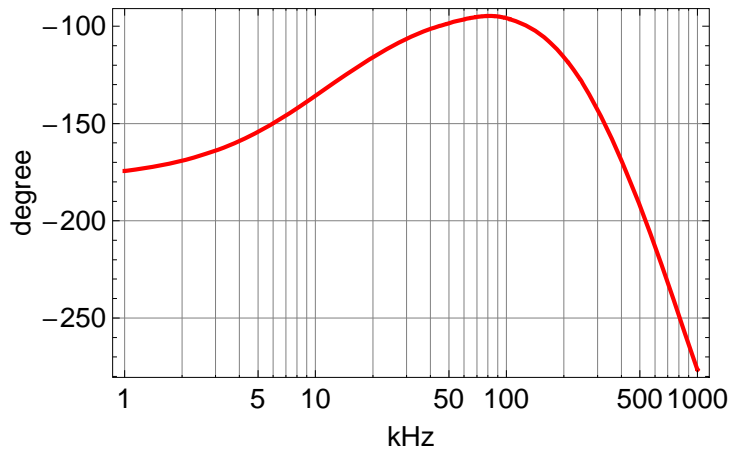


```
BodePlot[loop[0] /. f -> 1000 f, {f, 1, 1000}, MagnitudeRange -> All,  
PhaseRange -> All, XAxisLabel -> "kHz", PhaseReference -> -180,  
PlotStyle -> {Thickness [0.007], Red}, BaseStyle -> $TextStyle]
```

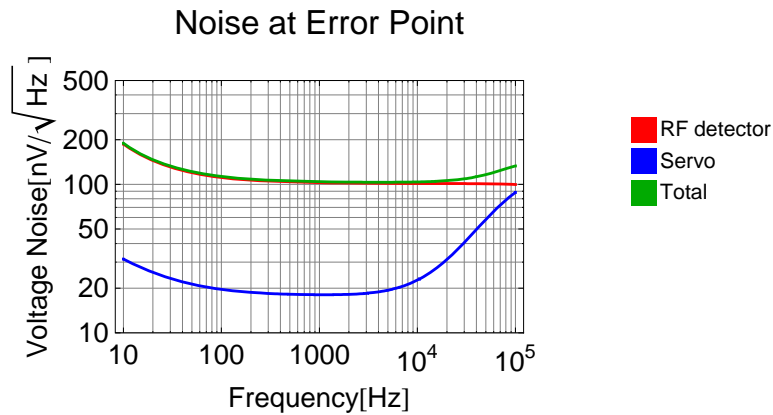
Magnitude



Phase




```
ShowLegend[LogLogPlot[{1*^9 totalnoise[2], 1*^9 opampnoise[0], 1*^9 loopnoise[0]},
  {f, 10, 1*^5}, FrameLabel -> {"Frequency[Hz]", "Voltage Noise[nV/√Hz]"},
  PlotLabel -> "Noise at Error Point", Frame -> True, PlotRange -> {10, 500},
  GridLines -> Automatic, PlotStyle -> {{Thickness[0.007], Red}, {Thickness[0.007], Blue},
  {Thickness[0.007], Darker[Green]}, {Thickness[0.007], Black}},
  BaseStyle -> $TextStyle, ImageSize -> Scaled[0.8]},
  {{Graphics[{Red, Rectangle[{1, 1}]}], "RF detector"}, {Graphics[{Blue, Rectangle[{1, 1}]}],
  "Servo"}, {Graphics[{Darker[Green], Rectangle[{1, 1}]}], "Total"}},
  BaseStyle -> {FontFamily -> "Helvetica", FontSize -> 10}, LegendPosition -> {0.85, -0.0},
  LegendSize -> {0.5, 0.3}, LegendTextSpace -> 5, LegendShadow -> None] // Quiet
```



Attenuator Chain

```
att = Solve[{{par[r1, r2 + par[r1, rt]] == rt,  $\frac{\text{par}[r1, rt]}{r2 + \text{par}[r1, rt]} == \text{FromdB}[-1.5]}$ }, {r1, r2}]
{{r2 -> 0.173554 rt, r1 -> 11.61 rt}}
```

rtt = 40*^3/11.61 (* termination *)

```
att /. rt -> rtt (* r2: series resistor; r1: resistor to GND *)
par[rtt, r1] /. att /. rt -> rtt (* last resistor in chain *)
3445.31
{{r2 -> 597.945, r1 -> 39 999.8}}
```

{3172.08}

```

FromdB[7×1.5] (* half the gain range *)
%gainadj (* initial gain drop *)
attfirst = Solve[{par[r1, r2 + par[r1, rt]] == rt,  $\frac{\text{par}[r1, \text{rt}]}{r2 + \text{par}[r1, \text{rt}]} == \%$ }, {r1, r2}]
attfirst /. rt → rtt (* First stage: r2: series; r1: to GND *)
par[r1, rr] /. att /. rr → r1 /. % /. rt → rtt (* combined 2nd res. to GND *)
3.34965
0.988141
{{r2 → 0.0119306 rt, r1 → 167.641 rt}}
{{r2 → 41.1047, r1 → 577576.}}
{{37409.1}}
vc /. Solve[{ $\frac{v}{r1} + \frac{v - v15}{r2} + \frac{v - vc}{r3} == 0$ ,  $\frac{vc - vcc}{r4} == \frac{vc - v}{r3}$ }, vc, v][[1]] // Expand
-  $\frac{r1 r4 v15}{r1 r2 + r1 r3 + r2 r3 - r1 r4 - r2 r4}$  +  $\frac{r1 r2 vcc}{r1 r2 + r1 r3 + r2 r3 - r1 r4 - r2 r4}$  +
 $\frac{r1 r3 vcc}{r1 r2 + r1 r3 + r2 r3 - r1 r4 - r2 r4}$  +  $\frac{r2 r3 vcc}{r1 r2 + r1 r3 + r2 r3 - r1 r4 - r2 r4}$ 
+  $\frac{r1 r2 vcc}{r1 r2 + r1 r3 + r2 r3 - r1 r4 - r2 r4}$  +
 $\frac{r1 r3 vcc}{r1 r2 + r1 r3 + r2 r3 - r1 r4 - r2 r4}$  +  $\frac{r2 r3 vcc}{r1 r2 + r1 r3 + r2 r3 - r1 r4 - r2 r4}$  // Simplify
 $\frac{(r2 r3 + r1 (r2 + r3)) vcc}{r2 (r3 - r4) + r1 (r2 + r3 - r4)}$ 

```