EE 538 Spring 2021
Low-Noise Analog Circuit Design
University of Washington Electrical & Computer Engineering

Instructor: Jason Silver
Assignment #2 (10 points)
Due Sunday, April 18 (Submit on Canvas as a Jupyter Notebook)

Please show your work

Problem 1: Photodiode amplifier design

Transimpedance amplifiers (TIAs) are frequently used as current-input amplifiers, wherein a feedback resistance R_f determines the TIA gain. Unfortunately, R_f forms a pole with both the photodiode capacitance and the input capacitance of the opamp, degrading phase margin and leading to peaking in the closed-loop amplifier response.

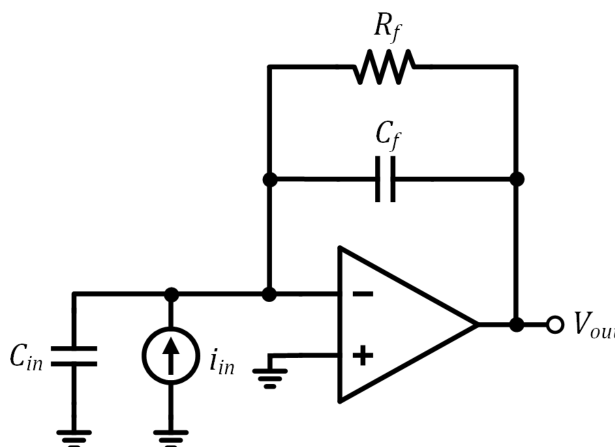


Figure 1. Current-input amplifier (TIA)

<u>*Analysis*</u>

The closed-loop transfer function of the uncompensated ($C_f = 0$) TIA can be expressed as

$$\frac{V_{out}}{i_{in}} = R_f \cdot \frac{A_{ol}(f)}{1 + A_{ol}(f) + sC_{in}R_f}$$

a) Determine an expression for the closed-loop transfer function of the compensated TIA (including C_f) assuming an opamp with a first-order response ($A_{ol}(f) = A_0/(1 + s/s_p)$, where A_0 is the DC gain of the opamp). What is the closed-loop resonant frequency (ω_0) of the TIA in terms of R_f, C_f, C_{in} and ω_u?

$$|s_p| = \omega_p \qquad = \omega_0$$

$$\omega_u = A_0\omega_p$$

$$C_{in} \gg C_f \qquad \text{so } C_f + C_{in} \approx C_{in}$$

1.

$$A_{OL}(f) = \frac{A_0}{1 + \frac{s}{s_p}}$$

2.

$$V_{out} = (V^+ - V^-) \cdot A_{OL}(f)\Big|_{V^+=0} = -V^- \cdot A_{OL}(f)$$

3.

$$\begin{aligned} Z_f &= R_f \parallel C_f \\ &= (\frac{1}{R_f} + sC_f)^{-1} \\ &= \frac{R_f}{1 + sR_fC_f} \end{aligned}$$

4.

$$\begin{aligned} i_{in} &= \frac{V^-}{Z_{in}} + \frac{V^- - V_{out}}{Z_f} \\ &= V^- sC_{in} + (V^- - V_{out})(\frac{1}{R_f} + sC_f) \\ &= V^-(sC_{in} + \frac{1}{R_f} + sC_f) - V_{out}(\frac{1}{R_f} + sC_f) \\ &= V^-(1 + \frac{sR_f(C_{in} + C_f)}{R_f}) - V_{out}(\frac{1 + sR_fC_f}{R_f}) \\ &= \frac{-V_{out}}{A_{OL}(f)}(1 + \frac{sR_f(C_{in} + C_f)}{R_f}) - V_{out}(\frac{1 + sR_fC_f}{R_f}) \\ &= \frac{-V_{out}}{A_{OL}(f)R_f}(1 + sR_f(C_{in} + C_f)) - \frac{V_{out}}{R_f}(1 + sR_fC_f) \\ &= \frac{-V_{out}}{A_{OL}(f)R_f}(1 + sR_f(C_{in} + C_f)) - \frac{V_{out}}{A_{OL}(f)R_f}A_{OL}(f)(1 + sR_fC_f) \end{aligned}$$

5.

$$\begin{aligned}
\frac{V_{out}}{i_{in}} &= \frac{-A_{OL}(f)R_f}{1+sR_f(C_{in}+C_f)+A_{OL}(f)(1+sR_fC_f)} \\
\frac{V_{out}}{i_{in}} &= \frac{-A_{OL}(f)R_f}{1+sR_fC_{in}+A_{OL}(f)(1+sR_fC_f)} \\
&= \frac{-\frac{A_0}{1+\frac{s}{s_p}}R_f}{1+sR_fC_{in}+\frac{A_0}{1+\frac{s}{s_p}}(1+sR_fC_f)} \\
&= \frac{-A_0R_f}{(1+\frac{s}{s_p})(1+sR_fC_{in})+\frac{A_0}{1+\frac{s}{s_p}}(1+sR_fC_f))} \\
&= \frac{-A_0R_f}{(1+\frac{s}{s_p})(1+sR_fC_{in})+A_0(1+sR_fC_f)} \\
&= \frac{-A_0R_f}{1+sR_fC_{in}+\frac{s}{s_p}+\frac{s^2}{s_p}R_fC_{in}+A_0+sA_0R_fC_f} \\
&= \frac{-A_0R_f}{(1+A_0)+s(\frac{1}{s_p}+R_fC_{in}+A_0R_fC_f)+\frac{s^2}{s_p}R_fC_{in}} \\
&\approx \frac{-R_f}{1+s(\frac{1}{A_0s_p}+\frac{R_fC_{in}}{A_0}+R_fC_f)+\frac{s^2}{A_0s_p}R_fC_{in}} \\
&\approx \frac{-R_f}{1+sR_fC_f+\frac{s^2}{A_0s_p}R_fC_{in}} \\
&\approx \frac{-R_f}{1+sR_fC_f+\frac{s^2}{\omega_u}R_fC_{in}}
\end{aligned}$$

$$\begin{aligned}
H(s) &= \frac{\omega_0^2}{s^2+2\zeta\omega_0\cdot s+\omega_0^2} \\
&= \frac{\omega_0^2}{s^2+\frac{s\cdot\omega_0}{Q}+\omega_0^2} \\
&= \frac{1}{\frac{s^2}{\omega_0^2}+\frac{s\cdot\omega_0}{Q}+1} \\
\frac{V_{out}}{i_{in}} &\approx -R_f\frac{1}{1+sR_fC_f+\frac{s^2}{\omega_u}R_fC_{in}} \\
\frac{1}{\omega_0^2} &= \frac{R_fC_{in}}{\omega_u} \\
\omega_0^2 &= \frac{\omega_u}{R_fC_{in}} \\
\omega_0 &= \sqrt{\frac{\omega_u}{R_fC_{in}}}
\end{aligned}$$

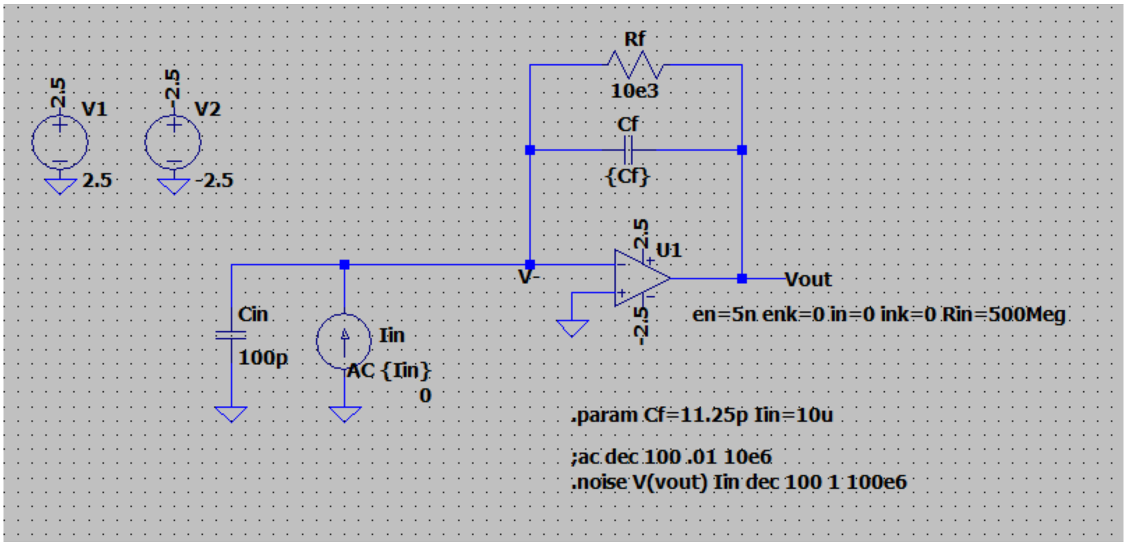
---

b) Show that choosing C_f such that $\frac{1}{R_f C_f} \approx \sqrt{\frac{\omega_u}{2 R_f C_{in}}}$ (assuming $C_{in} >> C_f$) results in a maximally flat (i.e. Butterworth) response.

$$
\begin{aligned}
H(s) &= \frac{1}{\frac{s^2}{\omega_0^2} + \frac{s}{Q\omega_0} + 1} \\
\omega_0 &= \sqrt{\frac{\omega_u}{R_f C_{in}}} \\
\frac{V_{out}}{i_{in}} &\approx -R_f \frac{1}{1 + sR_f C_f + \frac{s^2}{\omega_u} R_f C_{in}} \\
\frac{V_{out}}{i_{in}} &\approx -R_f \frac{1}{1 + sR_f C_f + \frac{s^2}{\omega_0^2}} \qquad \text{and Butterworth } Q = \frac{1}{\sqrt{2}} \\
\text{then} \quad & R_f C_f = \frac{1}{Q\omega_0} = \frac{\sqrt{2}}{\omega_0} \\
\sqrt{2} &= \sqrt{\frac{\omega_u}{R_f C_{in}}} R_f C_f \\
R_f C_f &= \frac{\sqrt{2}}{\sqrt{\frac{\omega_u}{R_f C_{in}}}} \\
&= \sqrt{2}\sqrt{\frac{R_f C_{in}}{\omega_u}} \\
&= \sqrt{\frac{2 R_f C_{in}}{\omega_u}} \\
\frac{1}{R_f C_f} &= \sqrt{\frac{\omega_u}{2 R_f C_{in}}} \\
C_f &= \frac{1}{R_f}\sqrt{\frac{2 R_f C_{in}}{\omega_u}} \\
&= \sqrt{\frac{2 C_{in}}{R_f \omega_u}} \\
&= \sqrt{\frac{2 C_{in}}{R_f A_0 \omega_p}} \\
&= \sqrt{\frac{2 C_{in}}{2\pi R_f A_0 f_p}} \\
C_f &= \sqrt{\frac{C_{in}}{\pi R_f A_0 f_p}}
\end{aligned}
$$

Design

c) Design the TIA in Figure 1 for a gain of $10k\Omega$ and a Butterworth response with a $3dB$ bandwidth of $2MHz$. Assuming C_{in} = $100pF$, what are the required values of ω_u (opamp GBW) and C_f? Verify your design in Ltspice.



Rf
10e3
Cf
{Cf}
V1
2.5
V2
-2.5
2.5
-2.5
U1
V-
Vout
Cin
100p
Iin
AC {Iin}
0
en=5n enk=0 in=0 ink=0 Rin=500Meg
.param Cf=11.25p Iin=10u
;ac dec 100 .01 10e6
.noise V(vout) Iin dec 100 1 100e6

1.

$$
\begin{aligned}
H(s) &= \frac{\omega_0^2}{s^2 + 2\zeta\omega_0 \cdot s + \omega_0^2} \\
&= \frac{1}{\frac{s^2}{\omega_0^2} + \frac{s}{Q\omega_0} + 1} \qquad \text{and Butterworth } Q = \frac{1}{\sqrt{2}} \\
|H(s)| &= \frac{1}{\sqrt{1 + \frac{\omega^4}{\omega_0^4}}} \\
\frac{1}{\sqrt{2}} &= \frac{1}{\sqrt{1 + \frac{\omega^4}{\omega_0^4}}}
\end{aligned}
$$

2.

$$
\begin{aligned}
\omega_{3dB_{CL}} &= \omega_0 \\
\omega_{3dB_{CL}} &= \sqrt{\frac{\omega_u}{R_f C_{in}}} \\
&= \sqrt{\frac{A_0 \omega_p}{R_f C_{in}}} \\
&= \sqrt{\frac{2\pi A_0 \cdot f_{3dB_{OL}}}{R_f C_{in}}}
\end{aligned}
$$

3.

$$
\begin{aligned}
2\pi f_{3dB_{CL}} &= \sqrt{\frac{2\pi A_0 \cdot f_{3dB_{OL}}}{R_f C_{in}}} \\
f_{3dB_{CL}} &= \sqrt{\frac{A_0 \cdot f_{3dB_{OL}}}{2\pi R_f C_{in}}} \qquad \text{and similarly}
\end{aligned}
$$

4.

$$
\begin{aligned}
f_{3dB_{OL}} &= 2\pi (f_{3dB_{CL}})^2 C_{in} \Big|_{A_0 = R_f} \\
\omega_u &= A_0 \omega_p \\
\omega_u &= A_0 \cdot 2\pi f_{3dB_{OL}}
\end{aligned}
$$

In [4]:

```
f3dbCL = 2*1e6
R_f = 10*1e3
C_in = 100*1e-12
A_0 = R_f
f3dbOL = 2*np.pi * f3dbCL**2 * C_in * R_f/A_0
omega_p = f3dbOL*2*np.pi
omega_u = A_0*omega_p  # gain bandwidth
omega_0 = np.sqrt(omega_u/(R_f*C_in))
C_f = sp.sqrt(2*C_in/(R_f*omega_u))

print(f'omega_u = {rnd(omega_u,2,"MHz")} MHz')
print(f'omega_0 = {rnd(omega_0,2,"MHz")} MHz')
print(f'C_f = {C_f} F')
```

```
omega_u = 157.91 MHz
omega_0 = 12.57 MHz
C_f = 1.12539539519638E-11 F
```

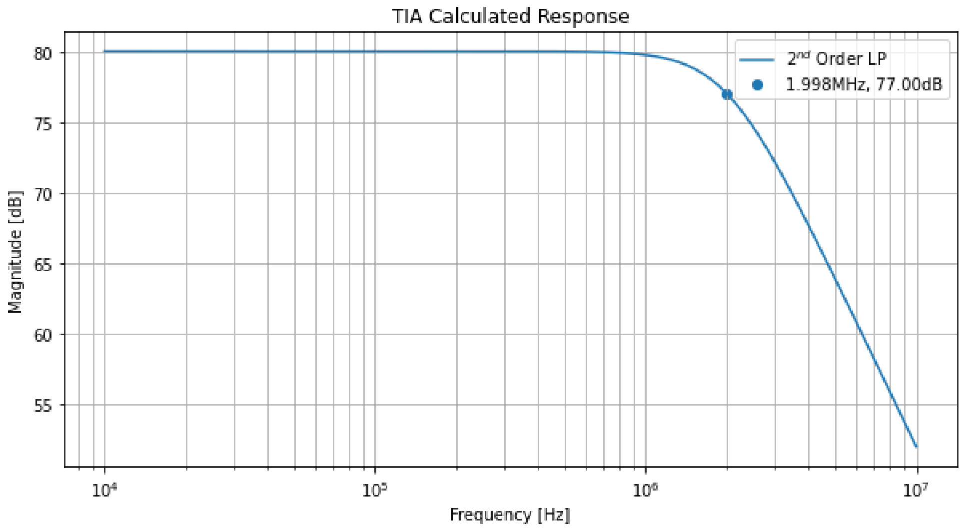
Calculated

In [5]:

```
s,R_f,C_f,C_in,A_0,omega_p,omega_0,omega_u,f3db = sp.symbols('s,R_f,C_f,C_in,A_0,omega_p,omega_
f = np.logspace(4, 7, 100000)
w = 2*np.pi*f

num = R_f
den = (R_f*C_in/(omega_u))*s**2 + (R_f*C_f)*s + 1

components = {
    R_f : 10*1e3,
    C_in: 100*1e-12,
    C_f : 1.1254e-11,
    omega_u: 157.91*1e6,
}
H = sp.Matrix([num/den])
H1 = H = H.subs(components)
H = lambdify(s,H,modules='numpy')
H = H(1j*w)
H = H[0][0]
```

In [6]:

```python
fig, ax = plt.subplots(figsize=(10,5))

x1 = np.where(20*np.log10(abs(H))<=max(20*np.log10(abs(H)))-3)[0][0]
label1 = "{:.3f}MHz, {:.2f}dB".format(rnd(f[x1],3,"MHz"), 20*np.log10(abs(H[x1])))

ax.set_title('TIA Calculated Response')
ax.semilogx(f, 20*np.log10(abs(H)),label=r'$2^{nd}$ Order LP')
ax.scatter(f[x1],20*np.log10(abs(H[x1])),label=label1,color='tab:blue')
ax.set_ylabel('Magnitude [dB]')
ax.set_xlabel('Frequency [Hz]')
ax.grid(which='both', axis='both')
ax.legend()
plt.show();
```



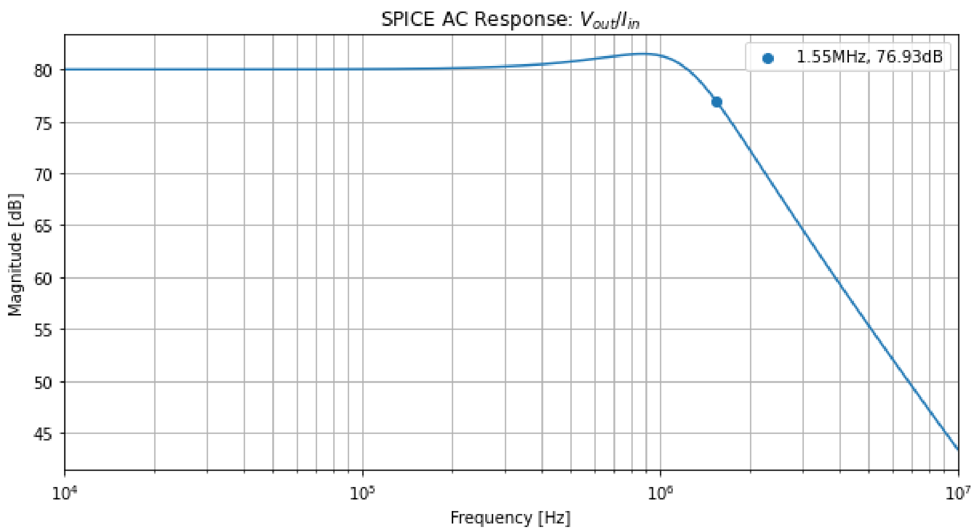
LTspice

In [7]:

```python
filepath = 'data/HW02.txt'
df = read_ltspice(filepath,'ac')
freq = df['Freq.']
mag = df['Mag_V(vout)/I(Iin)']
```

In [8]:

```python
fig, ax = plt.subplots(1,figsize=(10,5))

x1 = np.where(mag<=mag[0]-3)[0][0]
label1 = "{:.2f}MHz, {:.2f}dB".format(rnd(freq[x1],2,"MHz"), mag[x1])

ax.semilogx(freq, mag, color='tab:blue',label='')
ax.scatter(freq[x1],mag[x1],label=label1,color='tab:blue')
ax.grid(True,which='both')
ax.set_xlabel('Frequency [Hz]')
ax.set_ylabel('Magnitude [dB]')
ax.set_title(r'SPICE AC Response: $V_{out}/I_{in}$')
ax.set_xlim(1e4,1e7)

ax.legend()
plt.show();
```



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d) Assuming an opamp with $e_{na} = 5nV/\sqrt{Hz}$ and $i_{na} = 0$, determine an expression for the mean-squre input-referred noise current density i_n^2 of the TIA as a function of frequency (ignore bandwidth limitations of the TIA). Taking the TIA bandwidth into account, what is the maximum value of i_n? At what frequency do we see the maximum noise density? Verify in Ltspice.

Maximum noise density occurs at the 3dB cutoff frequency..

$$
\begin{aligned}
i_{na} &= 0 \\
e_{na} &= 5nV/\sqrt{Hz} \\
i_{nC} &= e_{na} \cdot 2\pi f C_{in} = \frac{5nV}{\sqrt{Hz}} \cdot 2\pi f \cdot 100\text{pf} \\
i_{sh}^2 &= 2qI_D\Delta f \\
i_n(f) &= \sqrt{(i_{sh})^2 + (\frac{e_{na}}{R_f})^2 + (\frac{\sqrt{4kTR_f}}{R_f})^2 + (i_{nC})^2} \\
&= \sqrt{(2qI_D)\Delta f + (\frac{e_{na}}{R_f})^2 + (\frac{\sqrt{4kTR_f}}{R_f})^2 + (e_{na} \cdot 2\pi f C_{in})^2} \\
&= \sqrt{(2qI_D)\Delta f + (\frac{e_{na}}{R_f})^2 + (\frac{4kT}{R_f}) + (e_{na} \cdot 2\pi f C_{in})^2} \\
i_n(f)^2 &= (2qI_D)\Delta f + (\frac{e_{na}}{R_f})^2 + (\frac{4kT}{R_f}) + (e_{na} \cdot 2\pi f C_{in})^2 \Big|_{f=f_{3dB}}
\end{aligned}
$$

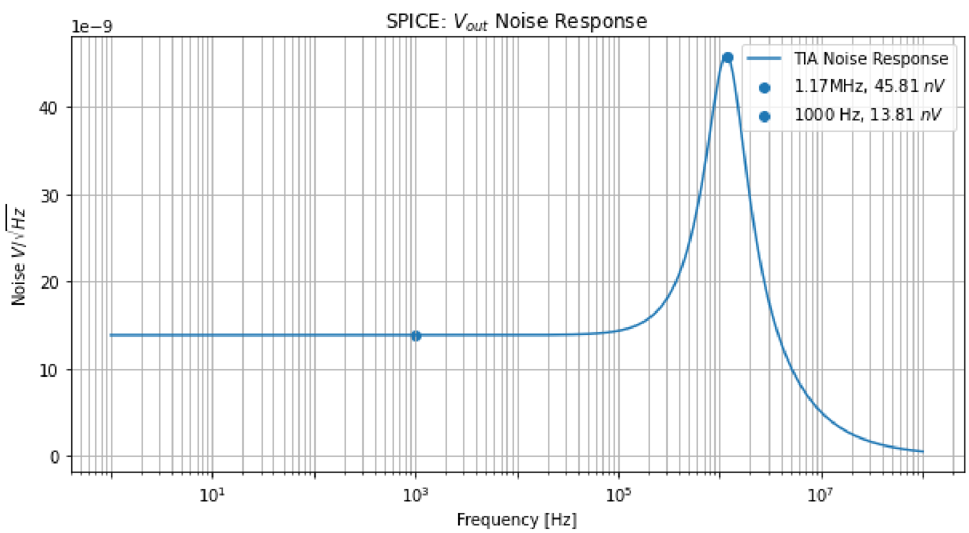
LTspice

In [9]:

```
filepath = 'data/HW02_noise.txt'
df = pd.read_csv(filepath)
freq = df['frequency']
mag = df['V(onoise)']
```

In [10]:

```
fig, ax = plt.subplots(1,figsize=(10,5))

x1 = np.where(freq<=1000)[0][-1]
label1 = r"1000 Hz, {:.2f} $nV$".format(mag[x1]*1e9)

x2 = mag.idxmax()
label2 =  r"{:.2f}MHz, {:.2f} $nV$".format(rnd(freq[x2],2,"MHz"),mag[x2]*1e9)

ax.semilogx(freq, mag, color='tab:blue',label='TIA Noise Response')
ax.scatter(freq[x2],mag[x2],label=label2,color='tab:blue')
ax.scatter(freq[x1],mag[x1],label=label1,color='tab:blue')
ax.grid(True,which='both')
ax.set_xlabel('Frequency [Hz]')
ax.set_ylabel(r'Noise $V/\sqrt{Hz}$')
ax.set_title(r'SPICE: $V_{out}$ Noise Response')
ax.ticklabel_format(style='sci', axis='y', scilimits=(-9,-9))
#ax.set_ylim(10e-9,50e-9)

# manipulate x-axis ticks and labels
ax.xaxis.set_major_locator(LogLocator(numticks=15)) #(1)
ax.xaxis.set_minor_locator(LogLocator(numticks=15,subs=np.arange(2,10))) #(2)
for label in ax.xaxis.get_ticklabels()[::2]:
    label.set_visible(False) #(3)

ax.legend()
plt.show();
```



e) If the TIA is driven by a photodiode with a DC current of $10\mu A$, what is the noise figure of the amplifier, in terms of noise density, at $1kHz$?

$$
\begin{aligned}
\text{NF} &= 10\log F \\
F &\equiv \frac{\text{total output noise power}}{\text{output noise due to input source}} \\
\text{total output noise power} &= (2qI_D)\Delta f + (\frac{e_{na}}{R_f})^2 + (\frac{4kT}{R_f}) + (e_{na}\cdot 2\pi f C_{in})^2 \\
\text{input source noise power} &= (2qI_D) \\
\text{Noise Figure} &= 38.37
\end{aligned}
$$

In [11]:

```
T = 298
k = 1.381 * 1e-23
q = 1.38 * 1e-23
I_D = 10*1e-6
f = 1000
e_na = 5*1e-9
Rf = 10*1e3
Cin = 100*1e-12

shot = (2*q*I_D)
amp = (e_na/Rf)**2
therm =  4*k*T/Rf
cap = (e_na *2*np.pi*f*Cin)**2


total_output = shot + amp + therm + cap
input_source = shot

NF = 10* np.log10(total_output/input_source)
print(f'Noise Figure = {round(NF,2)}')
```

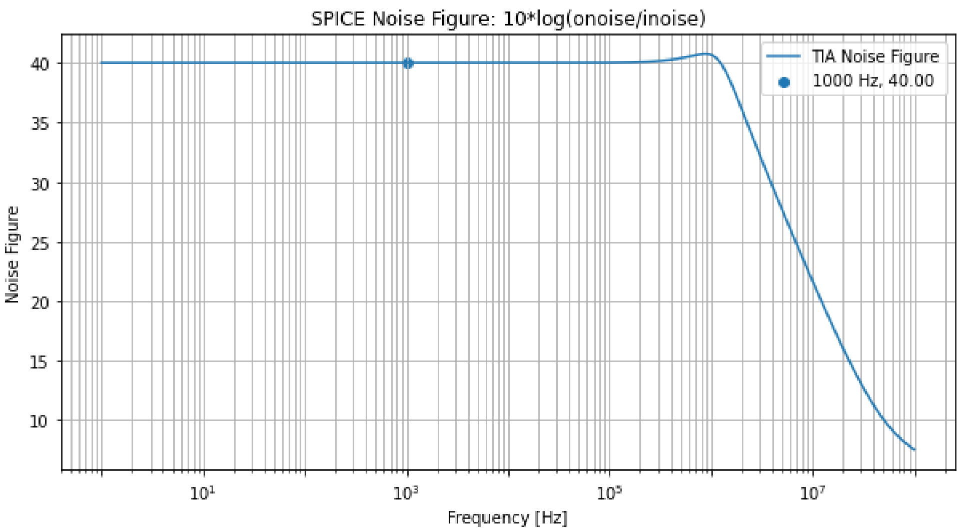
```
Noise Figure = 38.37
```

In [12]:

```
filepath = 'data/HW02_noise2.txt'
df = pd.read_csv(filepath)
freq = df['frequency']
onoise = df['V(onoise)']
inoise = df['inoise']
```

In [17]:

```
fig, ax = plt.subplots(1,figsize=(10,5))

x1 = np.where(freq<=1000)[0][-1]
label1 = r"1000 Hz, {:.2f}".format(10*np.log10(onoise[x1]/inoise[x1]))

ax.semilogx(freq, 10*np.log10(onoise/inoise), color='tab:blue',label='TIA Noise Figure')
ax.scatter(freq[x1],10*np.log10(onoise[x1]/inoise[x1]),label=label1,color='tab:blue')
ax.grid(True,which='both')
ax.set_xlabel('Frequency [Hz]')
ax.set_ylabel(r'Noise Figure')
ax.set_title(r'SPICE Noise Figure: 10*log(onoise/inoise)')
#ax.ticklabel_format(style='sci', axis='y', scilimits=(-9,-9))
#ax.set_ylim(10e-9,50e-9)

# manipulate x-axis ticks and labels
ax.xaxis.set_major_locator(LogLocator(numticks=15)) #(1)
ax.xaxis.set_minor_locator(LogLocator(numticks=15,subs=np.arange(2,10))) #(2)
for label in ax.xaxis.get_ticklabels()[::2]:
    label.set_visible(False) #(3)

ax.legend()
plt.show();
```



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Resources:

[https://www.analog.com/en/analog-dialogue/articles/compensating-current-feedback-amplifiers.html (https://www.analog.com/en/analog-dialogue/articles/compensating-current-feedback-amplifiers.html)](https://www.analog.com/en/analog-dialogue/articles/compensating-current-feedback-amplifiers.html)

[https://www.analog.com/en/technical-articles/transimpedance-amplifier-noise-considerations.html (https://www.analog.com/en/technical-articles/transimpedance-amplifier-noise-considerations.html)](https://www.analog.com/en/technical-articles/transimpedance-amplifier-noise-considerations.html)

[https://e2e.ti.com/support/amplifiers/f/amplifiers-forum/379953/open-loop-gain-vs-closed-loop-gain-in-tia (https://e2e.ti.com/support/amplifiers/f/amplifiers-forum/379953/open-loop-gain-vs-closed-loop-gain-in-tia)](https://e2e.ti.com/support/amplifiers/f/amplifiers-forum/379953/open-loop-gain-vs-closed-loop-gain-in-tia)

[https://www.allaboutcircuits.com/technical-articles/negative-feedback-part-8-analyzing-transimpedance-amplifier-stability/ (https://www.allaboutcircuits.com/technical-articles/negative-feedback-part-8-analyzing-transimpedance-amplifier-stability/)](https://www.allaboutcircuits.com/technical-articles/negative-feedback-part-8-analyzing-transimpedance-amplifier-stability/)

[https://www.embeddedcomputing.com/technology/analog-and-power/batteries-power-supplies/tia-fundamentals-the-noise-transfer-function-part-4 (https://www.embeddedcomputing.com/technology/analog-and-power/batteries-power-supplies/tia-fundamentals-the-noise-transfer-function-part-4)](https://www.embeddedcomputing.com/technology/analog-and-power/batteries-power-supplies/tia-fundamentals-the-noise-transfer-function-part-4)

[https://www.tij.co.jp/jp/lit/an/snoa942a/snoa942a.pdf?ts=1618760264451&ref_url=https%253A%252F%252Fwww.google.com%252F (https://www.tij.co.jp/jp/lit/an/snoa942a/snoa942a.pdf?ts=1618760264451&ref_url=https%253A%252F%252Fwww.google.com%252F)](https://www.tij.co.jp/jp/lit/an/snoa942a/snoa942a.pdf?ts=1618760264451&ref_url=https%253A%252F%252Fwww.google.com%252F)

https://e2e.ti.com/support/amplifiers/f/amplifiers-forum/504360/how-to-maintain-stability-of-a-tia-when-exceeding-the-open-loop-gain (https://e2e.ti.com/support/amplifiers/f/amplifiers-forum/504360/how-to-maintain-stability-of-a-tia-when-exceeding-the-open-loop-gain)

https://people.engr.tamu.edu/spalermo/ecen689_oi/lecture5_ee689_tias.pdf (https://people.engr.tamu.edu/spalermo/ecen689_oi/lecture5_ee689_tias.pdf)

https://2n3904blog.com/trans-impedance-amplifier-transfer-function/ (https://2n3904blog.com/trans-impedance-amplifier-transfer-function/)

http://www.seas.ucla.edu/brweb/papers/Journals/BR_SSCM_1_2019.pdf (http://www.seas.ucla.edu/brweb/papers/Journals/BR_SSCM_1_2019.pdf)

https://www.ti.com/lit/an/sboa122/sboa122.pdf?ts=1618932133586 (https://www.ti.com/lit/an/sboa122/sboa122.pdf?ts=1618932133586)

https://www.ti.com/lit/an/snoa515a/snoa515a.pdf?ts=1618912072084&ref_url=https%253A%252F%252Fwww.google.com%252F (https://www.ti.com/lit/an/snoa515a/snoa515a.pdf?ts=1618912072084&ref_url=https%253A%252F%252Fwww.google.com%252F)

$$\begin{aligned}
\frac{V_{out}}{i_{in}} &= \frac{Z_f A_{OL}(f)}{1 + \frac{Z_f}{Z_{C_{in}}} + A_{OL}(f)} \\
&= Z_f \frac{A_{OL}(f)}{1 + A_{OL}(f) + \frac{Z_f}{Z_{C_{in}}}} \\
&= Z_f \frac{1}{1 + \frac{1 + \frac{Z_f}{Z_{C_{in}}}}{A_{OL}(f)}} \\
&= Z_f \frac{1}{1 + \frac{1}{\beta A_{OL}(f)}} \qquad \text{where } \frac{1}{\beta} = 1 + \frac{Z_f}{Z_{C_{in}}} = 1 + \frac{(1 + sR_fC_f)sC_{in}}{R_f} = \frac{C_f C_{in} s^2}{R_f} + \frac{C_{in} s}{R_f} + 1
\end{aligned}$$

In [14]:

```
# Imports
import os
import sys
import cmath
import math
import matplotlib.pyplot as plt
import matplotlib
import numpy as np
import pandas as pd
import ltspice
import sympy as sp
from sympy.utilities.lambdify import lambdify
from scipy import signal
%matplotlib inline
from IPython.core.interactiveshell import InteractiveShell
InteractiveShell.ast_node_interactivity = "all"
from matplotlib.ticker import LogLocator
```

In [15]:

```
def read_ltspice(file_name,ftype='trans',units='db'):
    cols = []
    arrs = []
    with open(file_name, 'r',encoding='utf-8') as data:
        for i,line in enumerate(data):
            if i==0:
                cols = line.split()
                arrs = [[] for _ in cols]
                continue
            parts = line.split()
            for j,part in enumerate(parts):
                arrs[j].append(part)
    df = pd.DataFrame(arrs,dtype='float64')
    df = df.T
    df.columns = cols
    if ftype=='trans':
        return df
    elif ftype=='ac':
        if units=='db':
            for col in cols:
                if df[col].str.contains(',').all():
                    df[f'Mag_{col}'] = df[col].apply(lambda x: x.split(',')[0])
                    df[f'Mag_{col}'] = df[f'Mag_{col}'].apply(lambda x: x[1:-2])
                    df[f'Mag_{col}'] = df[f'Mag_{col}'].astype('float64')
                    df[f'Phase_{col}'] = df[col].apply(lambda x: x.split(',')[1])
                    df[f'Phase_{col}'] = df[f'Phase_{col}'].apply(lambda x: x[0:-2])
                    df[f'Phase_{col}'] = df[f'Phase_{col}'].astype('float64')
        if units=='cartesian':
            for col in cols:
                if df[col].str.contains(',').all():
                    df[f'Re_{col}'] = df[col].apply(lambda x: x.split(',')[0])
                    df[f'Re_{col}'] = df[f'Re_{col}'].astype('float64')
                    df[f'Im_{col}'] = df[col].apply(lambda x: x.split(',')[1])
                    df[f'Im_{col}'] = df[f'Im_{col}'].astype('float64')
        df['Freq.'] = df['Freq.'].astype('float64')
        return df
    else:
        print('invalid ftype')
```

In [16]:

```
def rnd(num,places,unit):
    if unit.lower()=='mhz':
        return round(num/(1e6),places)
```

In [ ]:

```

```