Given: \( N = 4 \), \( f_p = 500 \text{kHz} \) Pass band Edge
\( R_p = 0.3\text{dB} \) Pass band Attenuation.

Needed for Synthesis: \( N \), \( \omega_{-3\text{dB}} \)

Butterworth:

\[
|H(\omega)|^2 = \frac{1}{1 + \left(\frac{\omega}{\omega_{-3\text{dB}}}\right)^{2N}} = \frac{1}{1 + \varepsilon^2 \left(\frac{\omega}{\omega_p}\right)^{2N}}
\]

With \( \frac{1}{1 + \varepsilon^2} = (10^{-\frac{R_p}{20}})^2 \) Pass band Attenuation.

\[
\left(\frac{\omega}{\omega_{-3\text{dB}}}\right)^{2N} = \varepsilon^2 \left(\frac{\omega}{\omega_p}\right)^{2N}
\]

\( \Rightarrow \)

\[
\frac{\omega_{-3\text{dB}}}{\omega_p} = \frac{1}{\varepsilon^{1/N}}
\]

\( \varepsilon = \sqrt{10^{-\frac{R_p}{10}} - 1} = 0.2674 \)

\( \Rightarrow \)

\( \omega_{-3\text{dB}} = 2\pi \cdot 500\text{kHz} \cdot \frac{1}{0.2674^{1/4}} \)

\( \omega_{-3\text{dB}} = 2\pi \cdot 635.3 \text{kHz} \)
Implementation:

\[ H(s) = \frac{G \omega_0^2}{s^2 + \frac{s \omega_0}{Q} + \omega_0^2} \]

\[ \omega_0 = \frac{1}{\sqrt{R_1 C_1 R_2 C_2}} \]

\[ G = K \quad Q = \frac{\omega_0}{\frac{1}{R_1 C_1} + \frac{1}{R_2 C_2} + \frac{1-K}{R_2 C_2}} \]

From Matlab:

\[ \omega_0_1 = 4.3687 \text{ Mrad/s} \quad \omega_0_2 = 4.3687 \text{ Mrad/s} \]

\[ Q_1 = 0.5412 \quad Q_2 = 1.3066 \]

\[ G = K = 1, \text{ choose } R_1 = R_2 = R = R_{\text{max}} = 100k \text{ (Nom)} \]

\[ Q = \frac{\omega_0 R C_1}{2} \quad \text{(note that Q does not change with systematic RC variations!)} \]

\[ C_1 = \frac{2Q}{\omega_0 R^+} \quad \text{(maximum component values)} \]
\[ w_0 = \frac{1}{R \sqrt{C_1 C_2}} \]

**Worst Case:**
\[
R = R^+ = 1.15 R \\
C_1 = C_1^+ = 1.1 C_1 \\
C_2 = C_2^+ = 1.1 C_2
\]

\[ w_0 = \frac{1}{1.1 \cdot 1.15} \cdot \frac{1}{R \sqrt{C_1 C_2}} \]

\[
C_2^+ = \left( \frac{1}{w_0 R^+} \right)^2 \cdot \frac{1}{C_1^+}
\]

(maximum component values)

⇒ **Component Values See MATLAB Printout**

**Minimum Sampling Frequency:**

\[ |H(\omega)| \]

| 0 dB | -45 dB |

\[ H(f_s/2)^2 = \frac{1}{1 + \left( \frac{f_s}{2(f_s-3dB)} \right)^{2N}} \approx \left( \frac{2f^+}{f_s} \right)^{2N} \]

\[ f_s = \frac{2 f^+}{10^{-45 dB}} = \frac{2 \cdot 1.757 \cdot 695.3 \text{ kHz}}{10^{-45 dB}} \]

\[ f_s \geq 8.36 \text{ MHz} \]
MATLAB OUTPUT:

```
wo1 =
  4.3687e+006

wo2 =
  4.3687e+006

Q1 =
  0.5412

Q2 =
  1.3066

COMPONENT VALUES (MAX, NOM, MIN)

R =
  1.0e-005
  1.1500  1.0000  0.8500

C11 =
  1.0e-011
  0.2154  0.1959  0.1763

C12 =
  1.0e-011
  0.5201  0.4728  0.4256

C21 =
  1.0e-011
  0.1839  0.1672  0.1505

C22 =
  1.0e-012
  0.7517  0.6925  0.6232
```
$R_p = 0.3 \text{dB}$

$H(w)$

$w \text{ [rad]}$

$f_p = 500 \mu \text{Hz}$

SPEC
% filter specification and synthesis
N = 4;
Wn = 2*pi*695.3e3; % -3dB frequency [rad] (hand calculated)
[Z, P, K] = butter(N, Wn, 's');

% Plot frequency response and check vs. spec
w1 = 2*pi*100e3;
w2 = 2*pi*1000e3;
wp = 2*pi*509e3;
Ap = 10^(-0.3/20);
Amin = 0.5;

[NUM, DEN] = zp2tf(Z, P, K);
[H, W] = freqs(NUM, DEN);
loglog(W, abs(H), 'LineWidth',2);
axis([w1 w2 Amin 1.1]);
line([w1 wp], [Ap Ap], 'LineWidth',2, 'Color','red');
line([wp wp], [Ap Amin], 'LineWidth',2, 'Color','red');
title('EE247 HW2 Problem 1 - Passband Plot vs. Spec');
xlabel('w [rad]');
ylabel('|H(w)|');
grid;

% Break up into biquads
[NUM1, DEN1] = zp2tf([ ], P(1:2), 1);
[NUM2, DEN2] = zp2tf([ ], P(3:4), 1);
w01 = sqrt(DEN1(3));
w02 = sqrt(DEN2(3));
Q1 = w01/DEN1(2);
Q2 = w02/DEN2(2);

% Calculate component values
Rnom=100e3;
MR=1.15;
MC=1.1;
mR=0.95;
mC=0.9;

% Maximum component values
R(1) = Rnom*MR;
C11(1) = 2*Q1/(w01*R(1));
C12(1) = 2*Q2/(w02*R(1));
C21(1) = (1/C11(1)) + (1/(w01*R(1)))^2;
C22(1) = (1/C12(1)) + (1/(w02*R(1)))^2;

% Nominal component values
R(2) = R(1)/MR;
C11(2) = C11(1)/MC;
C12(2) = C12(1)/MC;
C21(2) = C21(1)/MC;
C22(2) = C22(1)/MC;

% Minimum component values
R(3) = R(2)*mR;
C11(3) = C11(2)*mC;
C12(3) = C12(2)*mC;
C21(3) = C21(2)*mC;
C22(3) = C22(2)*mC;

R
C11
C12
C21
C22
* EE247 Homework#2 - Problem 1
* Spectre Input
* Boris Murmann

********** Circuit Description **********

simulator lang=spectre

vin (vi 0) vsource mag=1

b1nom (vi volnom) skbp res=100k cap1=1.359p cap2=1.672p k=1
b2nom (volnom vonom) skbp res=100k cap1=4.728p cap2=0.6925p k=1

b1min (vi volmin) skbp res=85k cap1=1.763p cap2=1.505p k=1
b2min (volmin vonin) skbp res=85k cap1=4.728p cap2=0.6925p k=1

b1max (vi volmax) skbp res=115k cap1=3.154p cap2=1.839p k=1
b2max (volmax vonax) skbp res=115k cap1=5.201p cap2=0.762p k=1

subckt skbp (vi vo)
  parameters cap res cap1 cap2 k
    r1 (vi 1) resistor r=res
    r2 (2 1) resistor r=res
    c1 (1 vo) capacitor c=cap1
    c2 (2 0) capacitor c=cap2
    kl (vo 0 2 0) vcvvs gain=k
  ends skbp

********** Control Statements **********

SimOptions options
  + rawfmt= psfbin
  + gmin= 1E-12
  + reltol= 1E-03
  + vabstol= 1E-06
  + labstol= 1E-12
  + temp= 27

ACSweep ac start=100k stop=10M dec=100
Spectre Output - Problem 1

\[ |H(f)| \]

-0.3dB

SPEC

freq (Hz)

500kHz

100K

900m

920m

940m

960m

980m
2. \[ H_1(s) = \frac{-K_{oa}}{s + w_{oa}} \]
\[ H_2(s) = \frac{K_{2b}s^2 + K_{ob}}{s^2 + \frac{w_{ob}}{Q} + w_{ob}^2} \]
\[ K_{1b} = 0 \quad \text{(Complex conj. zeros)} \]

From Matlab:
\[ K \cdot \frac{(s-z_1)(s-z_2)}{(s-p_1)(s-p_2)(s-p_3)} \]
\[ \downarrow \quad \downarrow \]
\[ H_2(s) \quad H_1(s) \]

- \[ H_1(s=0) = -\frac{K_{oa}}{w_{oa}} = \frac{1}{5} = -1 \quad \text{(want unity gain)} \]
  \[ w_{oa} = \frac{-1}{p_3} \quad K_{oa} = w_{oa} \]

- Use \( \text{zp2tf} \left( \begin{bmatrix} z_1, z_2 \end{bmatrix}, \begin{bmatrix} p_1, p_2 \end{bmatrix}, K/K_{oa} \right) \)
  \[ \Rightarrow w_{ob}, Q, K_{ob}, K_{2b} \]

\[ \Rightarrow \]
\[ w_{oa} = 3.28 \text{ Mrad/s} = K_{oa} \]
\[ w_{ob} = 6.3 \text{ Mrad/s} \]
\[ Q = 2.21 \]
\[ K_{ob} = 3.97 \cdot 10^5 \]
\[ K_{2b} = 0.13 \frac{1}{\text{rad}^2} \]
Implementation:

- \( C_1 = \frac{1}{\omega_0 R_1} = 303.9 \text{ fF} \) with \( R_1 = R_{\text{max}} = 100k \)
- Iteratively scale \( C_A, C_B \) until all \( R < R_{\text{max}} \)
  
  **Using Matlab:**

  \[
  \begin{align*}
  R_{1a} &= 79.37k \\
  R_{2a} &= -35.68k \\
  R_{3a} &= 87.54k \\
  R_{4a} &= 79.37k \\
  C_A &= 400 \text{ fF} \\
  C_B &= 200 \text{ fF} \\
  C_6 &= 52.8 \text{ fF} > 50 \text{ fF}
  \end{align*}
  \]

  Simulation results see attached
% EE247 Homework#2 Problem 2
% Boris Murnann

% filter specification and synthesis

clear;
N = 3;
Rp = 1;
Rs = 40;
Wn = 2*pi*10^6; % cutoff frequency [rad]
[Z, P, K] = ellip(N, Rp, Rs, Wn, 's');

% Plot frequency response and check vs. spec
% Plot range
w1 = 2*pi*100e3;
w2 = 2*pi*500e6;
w0p = Wn;
ws = 2*pi*30e6;
Ap = 10^(^-Rp/20);
As = 10^(^-Rs/20);
Amin = 10^((-Rs-20)/20);
[NUM, DEN] = zp2tf(Z, P, K);
[H,W] = freqs(NUM, DEN, [w1:1000:1000:ws]);

subplot(2,1,1)
loglog(W, abs(H), 'LineWidth',2);
axis([w1 w2 Amin 1.1]);
% horizontal passband line
line([w1 w0p], [Ap Ap], 'LineWidth',1, 'Color','red');
% line([w1 ws], [1 1], 'LineWidth',1, 'Color','red');
% horizontal stopband line
line([ws w2], [As As], 'LineWidth',1, 'Color','red');
% vertical passband line
line([wp w2], [Ap Amin], 'LineWidth',1, 'Color','red');
% vertical stopband line
line([ws ws], [1 As], 'LineWidth',1, 'Color','red');
title('EE247 HW2 Problem 2 - Frequency Response vs. Spec');
xlabel('w [rad]');
ylabel('|H(w)|');
grid;

subplot(2,1,2)
loglog(W, abs(H), 'LineWidth',2);
axis([w1 w2 Ap-0.3 1.05]);
% horizontal passband line
line([w1 w0p], [Ap Ap], 'LineWidth',2, 'Color','red');
% line([w1 ws], [1 1], 'LineWidth',2, 'Color','red');
% horizontal stopband line
line([ws w2], [As As], 'LineWidth',2, 'Color','red');
% vertical passband line
line([wp w2], [Ap Amin], 'LineWidth',2, 'Color','red');
% vertical stopband line
line([ws ws], [1 As], 'LineWidth',2, 'Color','red');
title('EE247 HW2 Problem 2 - Passband Zoom');
xlabel('w [rad]');
ylabel('|H(w)|');
grid;

% Calculate Coefficients
% First order section
% Desired DC Gain is G2=1
G2=1;
w0a=-P(3);
K0a=G1*%w0a
% Second order section
% DC Gain is also one, by using K/K0b as the K parameter in zp2tf
[NUM1, DEN1] = zp2tf([Z(1:2)], P(1:2), K/K0a);
w0b=sqrt(DEN1(3))
Spectre Output - Problem 2

\[ |H(f)| / \text{dB} \]

0.0

\[ \text{c320(mag(wavew11s111()))} \]

1dB

-1.0

-2.0

-3.0

-4.0

100K  1M  10Meg  100M

freq (Hz)

SPEEC

A: \( |V| = 1.000 \)
Spectre Output - Problem 2

\[ |H(f)|/dB \]

- $c320(mag(wave11s1i1()))$

freq (Hz)

-10
-20
-30
-40
-50
-60
-10K
-1M
-10M
-100M
-1G

A: "$0V \rightarrow 0.000$"
* EE247 Homework#2 - Problem 2
* Spectre Input
* Boris Murmann

********** Circuit Description **********

* component values from matlab

parameters
+R1 = 100k
+C1 = 3.0389e-013
+CA = 4.0000e-013
+CB = 2.0000e-013
+R1a = 7.9366e+004
+R2a = -3.9683e+004
+R3a = 8.7539e+004
+R4a = 7.9366e+004
+C6 = 5.2853e-014

vin (vi 0) vsourse mag=1

r1x (vi 1) resistor r=R1a
r2x (2 3) resistor r=R2a
r3x (3 4) resistor r=R3a
r4x (1 4) resistor r=R4a
cax (3 4) capacitor c=CA
cbx (1 2) capacitor c=CB
c6x (vi 3) capacitor c=C6
amp1 (2 0 1 0) vccs gain=-1e6
amp2 (4 0 3 0) vccs gain=-1e6

r11 (4 5) resistor r=R1
r12 (5 vo) resistor r=R1
c1x (5 vo) capacitor c=C1
amp3 (vo 0 5 0) vccs gain=-1e6

********** Control Statements **********

SimOptions options
+ rwavefmt= psfbin
+ gmin= 1e-12
+ reltol= 1e-03
+ xreltol= 1e-06
+ iabstol= 1e-12
+ temp= 27

AC Sweep ac start=100k stop=500Meg dec=100
2. Design of a 3\textsuperscript{rd} order elliptic low-pass filter.

(a)

Design Specifications:
- Passband: 0-10 MHz
- Maximum attenuation in the passband: 1 dB
- \(R_{\text{max}}\): 100k\(\Omega\)
- Filter Type: Elliptic
- Gain at \(f=0\): 1

By using the MATLAB functions, we can get the transfer function of the desired filter as follow:

\[
H(s) = \left( \frac{\omega_c}{s + 0.5237\omega_c} \right) \left( \frac{0.0692s^2 + 0.5265\omega_c^2}{s^2 + 0.4545\omega_c s + 1.0053\omega_c^2} \right)
\]

When \(\omega_c\) is the cut-off frequency of the filter (1dB attenuation), which is desired to be 10MHz

Split it into two filters:

\[
H_1(s) = \frac{\omega_c}{s + 0.5237\omega_c}
\]

\[
H_2(s) = \frac{0.0692s^2 + 0.5265\omega_c^2}{s^2 + 0.4545\omega_c s + 1.0053\omega_c^2}
\]

Realizations

\(H_1(s)\) realization

We will realize \(H_1(s)\) using an opamp with negative feedback, which is shown below:
The transfer function of the filter is:

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{1}{R_1 C s + \frac{1}{R_2 C}}
\]  

(1)

Ignore the minus sign (just a 180° phase shift) and compare (1) with the \(H_3(s)\), we get:

\[
\begin{align*}
\frac{1}{R_1 C} &= \omega_c = 62.8 \text{ Mrad/Sec} \\
\frac{1}{R_2 C} &= 0.5237 \omega_c = 32.9 \text{ Mrad/Sec}
\end{align*}
\]

(2)

Please note that the maximum realizable resistor is 100kΩ.

Solve (2) with the condition above and try to minimize the size of the capacitor, we have

\[
\begin{align*}
R_1 &= 52.4k\Omega \\
R_2 &= 100k\Omega \\
C &= 304 \text{ fF}
\end{align*}
\]

\(H_3(s)\) realization

We will use the Tow-Thomas biquad to realize \(H_3(s)\), a circuit diagram of the biquad is given below:
The transfer function is:

\[ \frac{V_{out}}{V_{in}} = \frac{b_3 s^2 + b_1 s + b_0}{s^2 + a_1 s + a_0} \]  \hspace{1cm} (3)

Where:

\[ b_0 = \frac{R_8}{R_3 R_4 R_7 C_1 C_2}, \quad b_1 = \frac{1}{R_4 C_1} \left( \frac{R_8}{R_6} - \frac{R_4 R_7}{R_6} \right), \quad b_2 = \frac{R_8}{R_6}, \quad a_0 = \frac{1}{R_1 C_1}, \quad a_1 = \frac{R_8}{R_2 R_5 R_7 C_1 C_2} \]

Compare (3) with the transfer function of the \( H_2(s) \), we get

- \( b_2 = 0.0692 \)
- \( b_1 = 0 \)
- \( b_0 = 0.5265 \times (2\pi \times 10 \text{ Mrad/Sec})^2 = 2.079 \times 10^3 \text{ (Mrad/Sec)}^2 \)
- \( a_1 = 0.4545 \times 2\pi \times 10 \text{ Mrad/Sec} = 28.56 \text{ Mrad/Sec} \)
- \( a_0 = 1.0053 \times (2\pi \times 10 \text{ Mrad/Sec})^2 = 3.969 \times 10^3 \text{ (Mrad/Sec)}^2 \)

Now solve the set of the equations above, keep in mind that the \( C_{min} = 50 \text{ fF} \), \( R_{max} = 100 \text{ k\Omega} \), and we try to minimize the total capacitor area.

Select:

\( R_1 = R_3 = R_6 = 100 \text{ k\Omega} \), \( C_2 = 50 \text{ fF} \)

So we get:

\[ C_1 = \frac{1}{a_1 R_{1,\text{max}}} = \frac{1}{(28.56 \text{ Mrad/Sec}) (100 \text{ k\Omega})} = 350 \text{ fF} \]

\[ R_3 = b_2 R_6 = (0.0692)(100 \text{ k\Omega}) = 6.92 \text{ k\Omega} \]

\[ R_4 R_7 = R_5 R_6 = (100 \text{ k\Omega})(100 \text{ k\Omega}) \Rightarrow R_4 = R_7 = 100 \text{ k\Omega} \]

\[ R_5 = \frac{R_8}{b_3 R_3 R_7 C_1 C_2} = \frac{6.92 \text{ k\Omega}}{(2.079 \times 10^{15} \text{ Sec}^{-2})(100 \text{ k\Omega})^2 (50 \text{ fF})(350 \text{ fF})} = 19.02 \text{ k\Omega} \]

\[ R_2 = \frac{b_0}{a_0} R_3 = \frac{2.079}{3.969} (1.902 \text{ k\Omega}) = 9.96 \text{ k\Omega} \]

Total Capacitance (\( H_1(s) \) and \( H_2(s) \))

\[ C_{TOT} = 350 \text{ fF} + 50 \text{ fF} + 304 \text{ fF} = 704 \text{ fF} \]
(b) When we placed the $H_2(s)$ in front of the $H_1(s)$, (see figure below), the total output noise kept increasing as we increased the upper frequency limit for integrating noise.

![Block Diagram](image)

For $f = 0$-100MHz, \( V_n \text{ (rms)} = 199 \mu V \)
For $f = 0$-1GHz, \( V_n \text{ (rms)} = 396 \mu V \)
For $f = 0$-10GHz, \( V_n \text{ (rms)} = 1.15 \text{ mV} \) (This is already too much) #

The total output noise increased without limit because there is no load capacitance connected to the output node of the $H_2(s)$.

So, for the better result (expected), we inverted the order of the first and second order sections. The simulation result in this case is much better. The output noise seems to have its saturation limit.

For $f = 0$-100MHz, \( V_n \text{ (rms)} = 230 \mu V \)
For $f = 0$-1GHz, \( V_n \text{ (rms)} = 233 \mu V \)
For $f = 0$-10GHz, \( V_n \text{ (rms)} = 233 \mu V \) (Saturated) #

(c)

If we try to keep the frequency response of the circuit to be constant, we will have the relationship:

\[
V_n \text{ (rms)} \propto \sqrt{R} \\
V_n \text{ (rms)} \propto \frac{1}{\sqrt{C}}
\]

We want to decrease the total output noise from 233 uV to 50 uV, so we have to scale up the sizes of the resistors and scale down the sizes of the capacitors by the factor of:

\[
\text{Scale Factor} = \left( \frac{233}{50} \right)^2 = 22 
\]

For the $H_2(s)$

\[
R_1 = 52.42 \text{ k}\Omega/22 = 38 \text{ k}\Omega, \\
R_2 = 100 \text{ k}\Omega/22 = 4.55 \text{ k}\Omega \\
C = 304\text{fF} \times 22 = 6.69 \text{ pF}
\]
For the \(H_2(s)\)

\[
R_1 = R_3 = R_4 = R_6 = R_7 = 100 \text{ k}\Omega / 22 = 4.55 \text{ k}\Omega
\]
\[
R_2 = 9.92 \text{ k}\Omega / 22 = 453 \Omega
\]
\[
R_5 = 19.02 \text{ k}\Omega / 22 = 864 \Omega
\]
\[
R_4 = 6.92 \text{ k}\Omega / 22 = 315 \Omega
\]
\[
C_1 = 350 \text{ pF} \times 22 = 7.7 \text{ pF}
\]
\[
C_2 = 50 \text{ fF} \times 22 = 1.1 \text{ pF}
\]

Form the SPICE simulations; we get the total output noise as follow:

- For \(f = 0-100\text{MHz}\), \(V_n (\text{rms}) = 49.1 \mu\text{V}\)
- For \(f = 0-1\text{GHz}\), \(V_n (\text{rms}) = 49.7 \mu\text{V}\)
- For \(f = 0-10\text{GHz}\), \(V_n (\text{rms}) = 49.7 \mu\text{V}\) (Saturated)

(d)

Firstly, try opamps with these specifications:

- Unity-Gain Bandwidth, \(f_u\) \(1\text{GHz}\)
- Input referred thermal noise, \(V_{n,\text{in}}\) \(4nV/\sqrt{Hz}\)

The simulation result shows that the frequency response of the filter has been changed because of the non-ideal opamps (see figure below). We may compensate this change by modifying the component values. However, we will neglect it now and we will do everything again to see what will happen if we want the better opamp that make the response almost unchanged.
Total output noise obtained from the simulation:

\[ V_n \text{ (rms)} = 168 \mu V \]

The amount of noise contributed by opamp is:

\[ V_{\text{opamp}} \text{ (rms)} = \sqrt{(168 \mu V)^2 - (50 \mu V)^2} = 160 \mu V \]

We want the total noise to be 100 \mu V
So we have to decrease the noise from the opamps to:

\[ V_{\text{opamp, new}} \text{ (rms)} = \sqrt{(100 \mu V)^2 - (50 \mu V)^2} = 86.6 \mu V \]

So the input referred noise have to be changed to:

\[ V_{n,\text{in}} \text{ (rms)} = \frac{86.6}{160} \times 4 nV/\sqrt{Hz} = 2.16 nV/\sqrt{Hz} \]

By using the new input referred noise value, the total output noise obtained by SPICE is:

\[ V_n \text{ (rms)} = 99.5 \mu V \]

⇒ A part that meets the specifications is MAX4223 from Maxim, which has the characteristics as follow:

Unity-Gain Bandwidth, \( f_o \) \hspace{1cm} 1GHz
Input voltage noise at \( f = 10 \text{kHz} \) \hspace{1cm} 2n \( nV/\sqrt{Hz} \)

If we want the frequency response to be almost unchanged

⇒ From the spice simulations, we need a 10GHz unity-gain opamp bandwidth to guarantee less than 3% changing of the cutoff frequency.

⇒ By scaling the value from the previous calculation result, the required input referred voltage noise is

\[ V_{\text{n,in}} = \left(2.16 nV/\sqrt{Hz}\right) \left(\frac{1}{\sqrt{10}}\right) = 0.68 nV/\sqrt{Hz} \]

⇒ It is virtually impossible to find any parts that meet the requirements in this case (10GHz Unity-Gain BW, 0.68 \( nV/\sqrt{Hz} \) input referred noise).