Hello, and welcome to the TI Precision Lab discussing op amp bandwidth, part 3.

In this video we'll discuss why you should always use the non-inverting gain to calculate bandwidth and secondary effects (namely high-frequency pole location) on bandwidth.

Dominant Pole

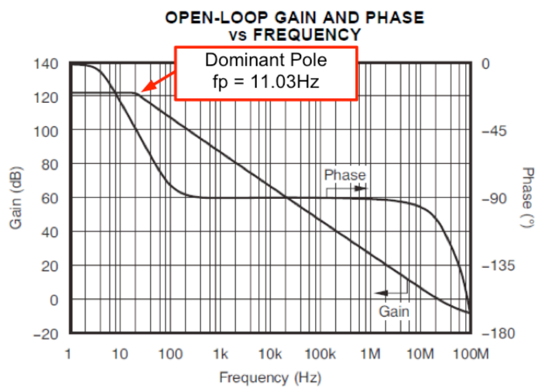
PARAMETER		CONDITIONS	STANDARD GRADE OPA827AI			HIGH GRADE OPA827I(1)(2)			UNIT
			MIN	TYP	MAX	MIN	TYP	MAX	
FREQUENCY RESPONSE									
Gain-Bandwidth Product	GBW	G = +1		22			22		MHz

$$\text{Dominant\_Pole} = \frac{\text{GBW}}{A_{vol}}$$

where
Dominant_Pole -- low frequency pole in Aol curve
GBW -- Gain Bandwidth in Hz
BW -- Bandwidth in Hz

$$A_{vol} = 10^{\frac{126}{20}} = 1.995 \times 10^6$$

$$\text{Dominant\_Pole} = \frac{\text{GBW}}{A_{vol}} = \frac{22\text{MHz}}{1.995 \times 10^6} = 11.03\text{Hz}$$



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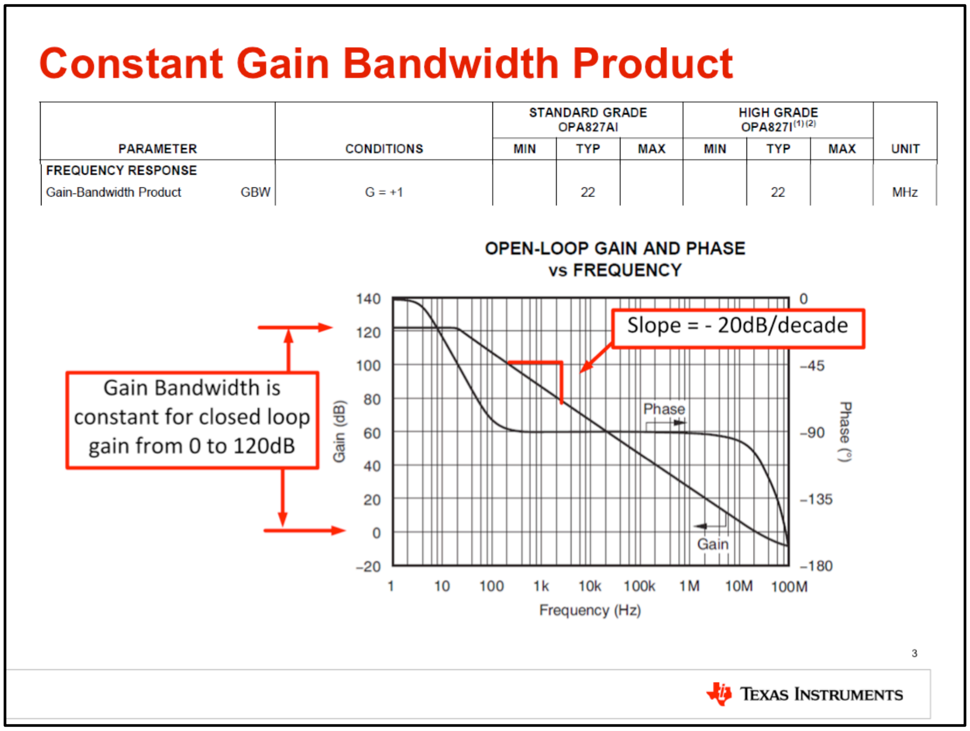
TEXAS INSTRUMENTS

In part 2 of this series we discussed the definition of gain bandwidth product. We demonstrated how to graphically determine the bandwidth of a circuit for a particular gain using the open-loop gain, or Aol, graph from a data sheet. However, we did not discuss the low-frequency, or dominate pole that appears in the graph.

The dominate pole is the point on the Aol graph where Aol begins to roll off with frequency. This parameter is important when developing macromodels. The frequency of the pole can be estimated from the Aol curve, but a more accurate approach is to calculate it using this equation, where GBW is the gain bandwidth product and Avol is the open loop gain of the device.

Using the OPA827 as an example, we find the device has a gain bandwidth product of 22MHz and open loop gain of 126 decibels. We can convert 126dB to its linear representation using this equation.

Substituting 22MHz and 1.995 times 10 to the 6th for gain bandwidth and open loop gain, respectively, yields a dominate pole frequency of 11.03Hz. This calculation is consistent with the graph from the data sheet.

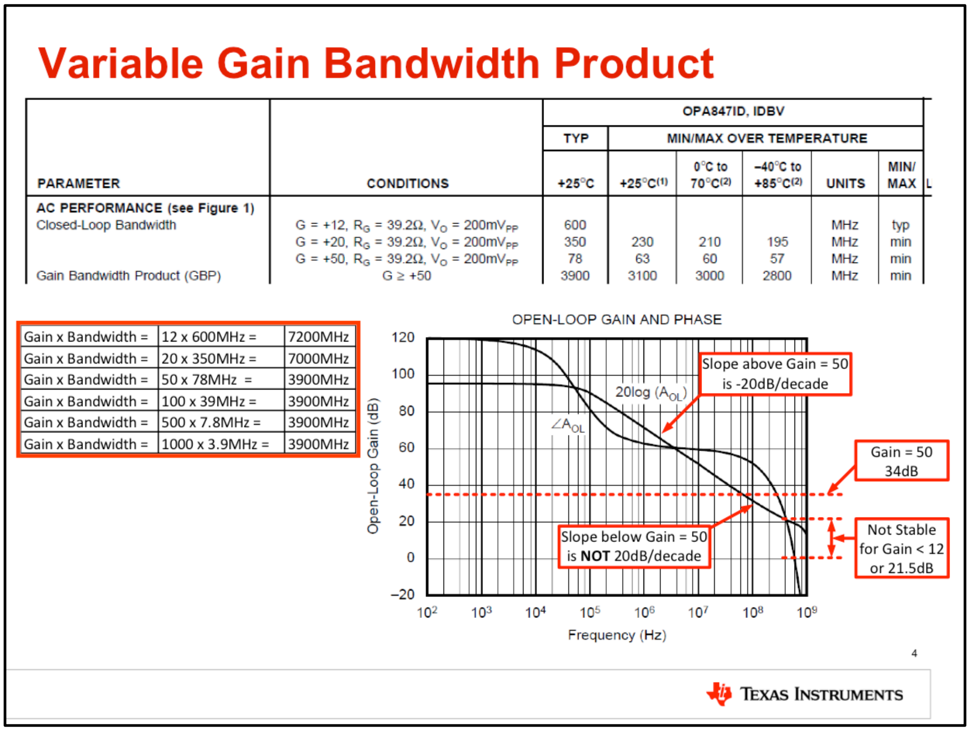


In this slide we further examine the OPA827 open loop gain curve. We see that the dc open loop gain is 120dB and remains constant until we reach the dominant pole. At frequencies greater than the dominant pole, the open loop gain decreases at a rate of -20dB per decade. Notice that for the OPA827 the slope of Aol is constant until we cross unity gain. Therefore the gain bandwidth product is constant for closed loop gains from 0 to 120 decibels.

While it is common to have open loop gain curves decrease at a constant rate of 20dB per decade, it is not always the case. For example, let's take a look at the high-speed OPA847.

Original notes:

This slide emphasizes the fact that gain bandwidth is only defined over the range where Aol rolls off at a rate of 20dB/decade. In this example Gain Bandwidth is defined over the entire range of Aol (0dB to 120dB). Later we will show an example where gain bandwidth is not defined.



Variable Gain Bandwidth Product

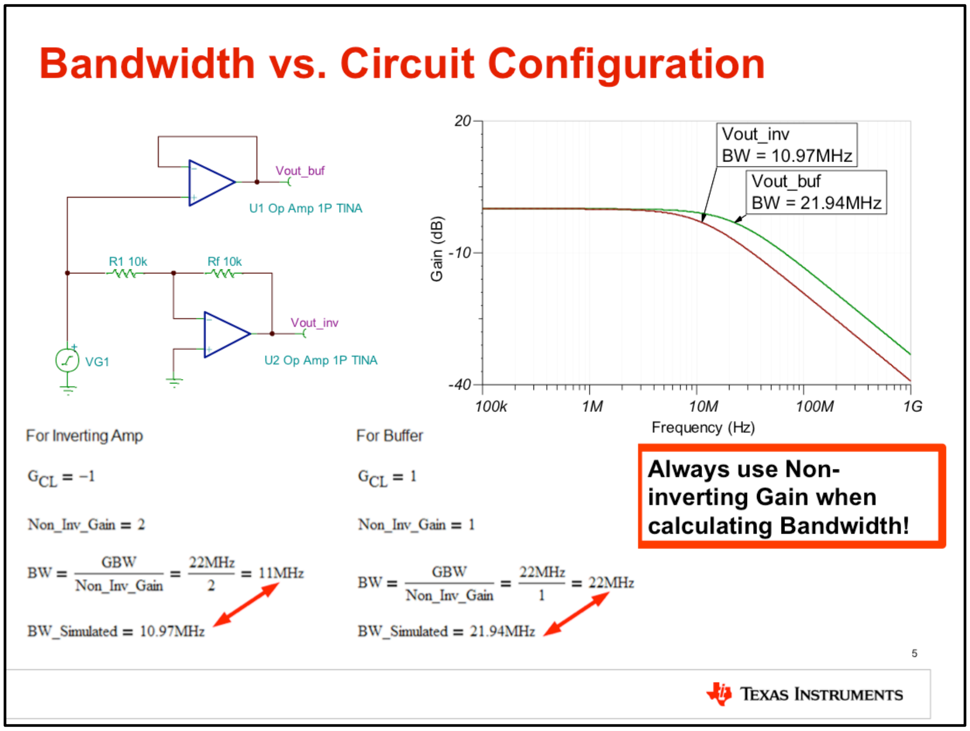
PARAMETER	CONDITIONS	OPA847ID, IDBV TYP +25°C	MIN/MAX OVER TEMPERATURE +25°C(1)	0°C to 70°C(2)	−40°C to +85°C(2)	UNITS	MIN/MAX
AC PERFORMANCE (see Figure 1)							
Closed-Loop Bandwidth	G = +12, R_G = 39.2Ω, V_O = 200mV_{PP}	600				MHz	typ
	G = +20, R_G = 39.2Ω, V_O = 200mV_{PP}	350	230	210	195	MHz	min
	G = +50, R_G = 39.2Ω, V_O = 200mV_{PP}	78	63	60	57	MHz	min
Gain Bandwidth Product (GBP)	G ≥ +50	3900	3100	3000	2800	MHz	min

Gain x Bandwidth =	12 x 600MHz =	7200MHz
Gain x Bandwidth =	20 x 350MHz =	7000MHz
Gain x Bandwidth =	50 x 78MHz =	3900MHz
Gain x Bandwidth =	100 x 39MHz =	3900MHz
Gain x Bandwidth =	500 x 7.8MHz =	3900MHz
Gain x Bandwidth =	1000 x 3.9MHz =	3900MHz

This slide shows the Aol curve for the OPA847, whose gain bandwidth product is defined for only a portion of the Aol curve. In this case it's defined only for closed loop gains greater than 50V/V.

Looking at the open loop gain curve, we see that for gains greater than 50V/V, or 34dB, the slope of the Aol curve is -20dB/decade. Therefore the gain bandwidth product is equal to 3900MHz for all closed loop gains greater than 50V/V.

However, as the gain decreases below 50V/V, the slope of Aol changes. Therefore, there is no gain bandwidth product specified. Instead, the closed loop bandwidth for particular gains is specified. Also notice that for gains less than 12V/V the phase margin indicates that the device is not stable. The table illustrates how the product of the gain and bandwidth is not constant for gains less than 50V/V, but is constant for gains of 50 or greater.

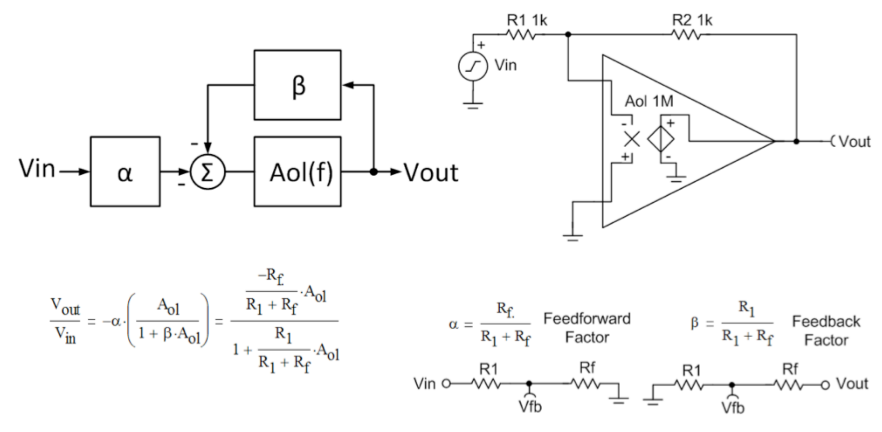


In part 2 we calculated closed loop bandwidth for a non-inverting configuration using the gain bandwidth product. You might be surprised to learn that the bandwidth calculation for the *inverting* configuration is calculated using the *non-inverting gain*. Note that the non-inverting gain is typically referred to as noise gain.

This example shows the same amplifier connected in both an inverting and non-inverting configuration. The inverting configuration has a gain of -1 and the non-inverting configuration has a gain of +1. Let's start by calculating the bandwidth for the non-inverting configuration. The bandwidth for the non-inverting amplifier U1 is calculated by taking the gain bandwidth product and dividing by the non-inverting gain. So, for this example, the bandwidth is 22MHz divided by 1 which is equal to 22MHz.

On the other hand, the bandwidth of the inverting amplifier, U2, is calculated using the *non-inverting gain*. The gain with respect to the non-inverting input is calculated as Rf/R1 +1, which is 2 in this example. So, the bandwidth of the inverting amplifier is 22MHz divided by 2 which is 11MHz. A common mistake is to consider the gain seen by the signal source rather than the noise gain for bandwidth calculations involving inverting amplifiers.

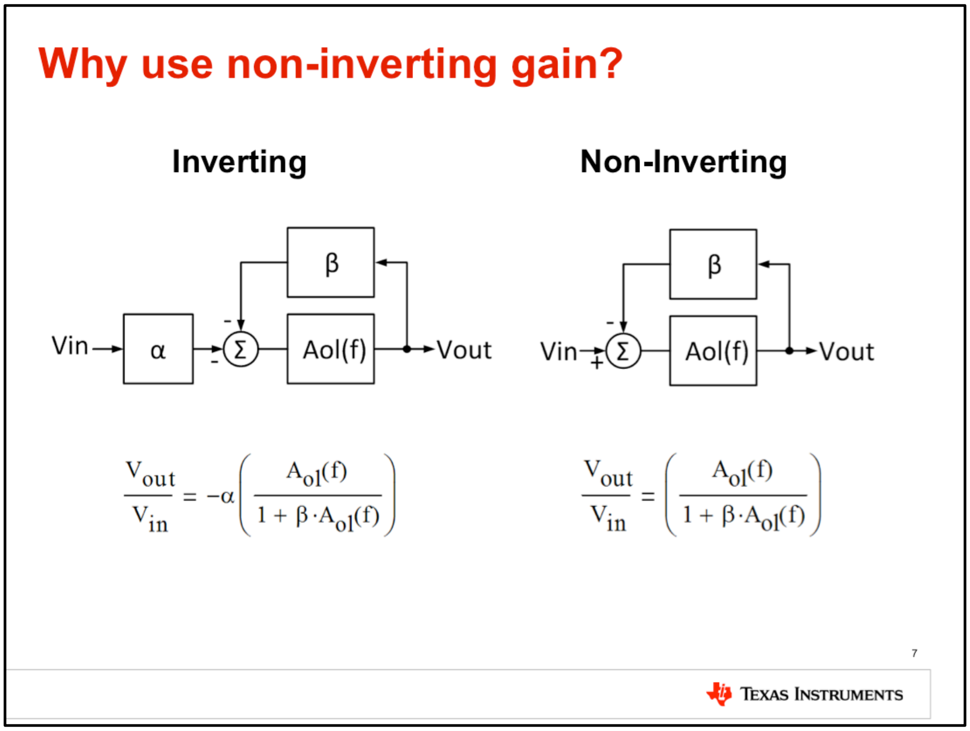
This example is simulated to prove that the hand calculations are correct. Notice that



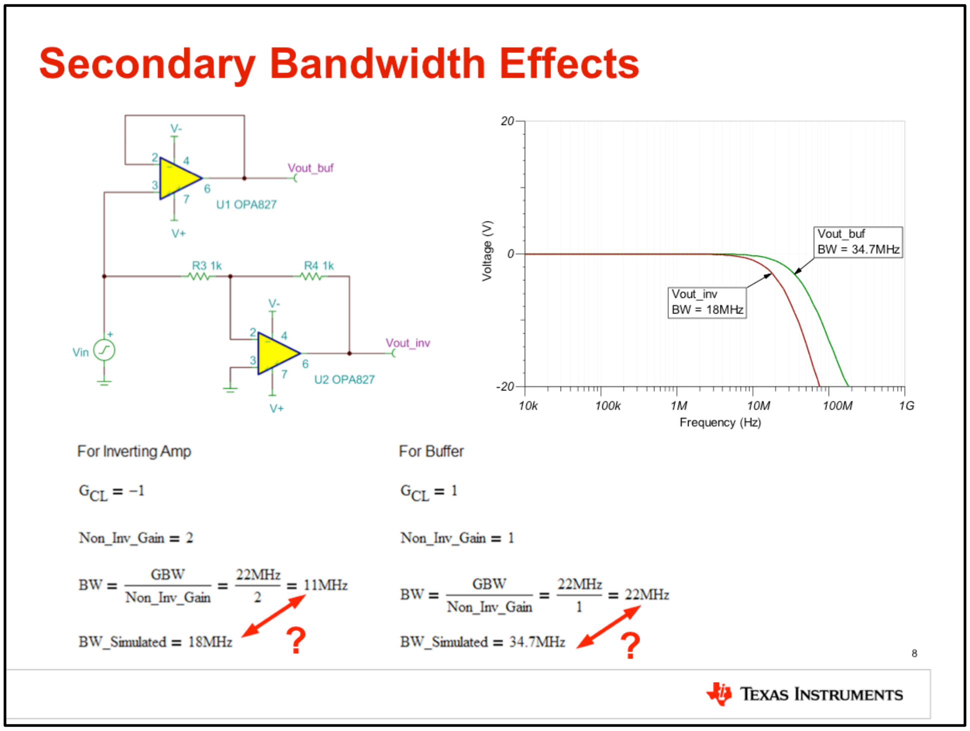
$$\frac{V_{out}}{V_{in}} = -\alpha\cdot\left(\frac{A_{ol}}{1+\beta\cdot A_{ol}}\right) = \frac{\frac{-R_f}{R_1+R_f}\cdot A_{ol}}{1+\frac{R_1}{R_1+R_f}\cdot A_{ol}}$$

$$\alpha = \frac{R_f}{R_1+R_f} \quad \text{Feedforward Factor} \qquad \beta = \frac{R_1}{R_1+R_f} \quad \text{Feedback Factor}$$

On the previous slide we demonstrated that you always need to use the non-inverting gain, or noise gain, when doing bandwidth calculations. This leads one to wonder what the theoretical basis is for always using noise gain regardless of the circuit configuration. First lets consider the inverting configuration. The transfer function can be derived using either the controls system representation shown on the left or the circuit representation on the right. The controls system representation is intuitive so let’s focus on that. The transfer function of inverting configuration is AOL divided by 1 + AOL x Beta multiplied by the feed forward factor alpha. AOL is the only term in this equation that changes with frequency. Now let’s compare the inverting and non-inverting configuration.



Here we compare the inverting and non-inverting configuration. Notice that the only difference between the two configurations is the feed forward factor alpha. Alpha is a constant scalar and does not affect bandwidth. The bandwidth is determined by the quantity Aol divided by 1 + Beta x Aol. This term is the same for both the inverting and non-inverting configuration. Furthermore, since Aol is the same in both cases, the bandwidth is set by Beta. Remember from the previous video, that 1/Beta is the non-inverting gain and equals Rf/R1 +1. Thus, the non-inverting gain sets the bandwidth for both the inverting and non-inverting configuration.



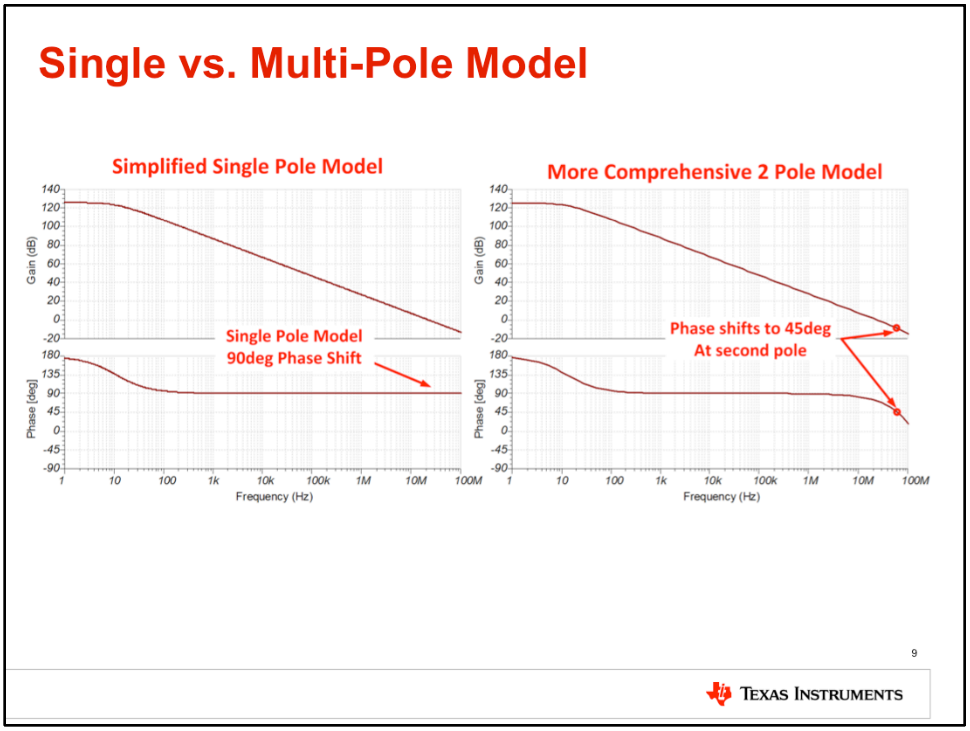
Now let's take a look at secondary bandwidth effects.

In this simulation we again have a buffer with a gain of 1V/V and an inverting amplifier with gain of -1V/V. These are the same circuit configurations as shown previously. The only difference, however, is that the amplifiers in this simulation are OPA827 macomodels, whereas the previous simulation used a simplified single pole op amp model.

The calculation of BW is the same as before. Using the non-inverting gains we calculate bandwidths of 11MHz for the inverting amplifier and 22MHz for the buffer.

When we simulate the circuits, however, the bandwidths are 18MHz and 34.7MHz. Neither of these match the calculation. Why?

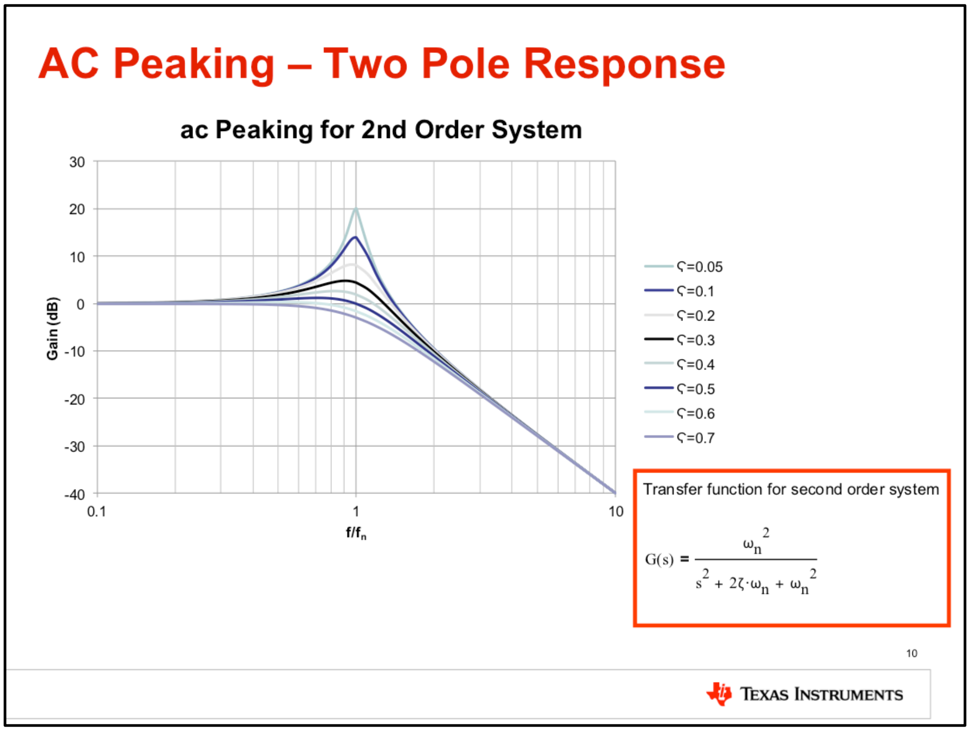
Real-world amplifiers and robust simulation models have multiple poles in their open loop gain, or Aol curves. We have already discussed the presence of a low-frequency, or dominate pole. The other poles are typically placed outside the unity gain bandwidth of the device. However, they can still affect the bandwidth.



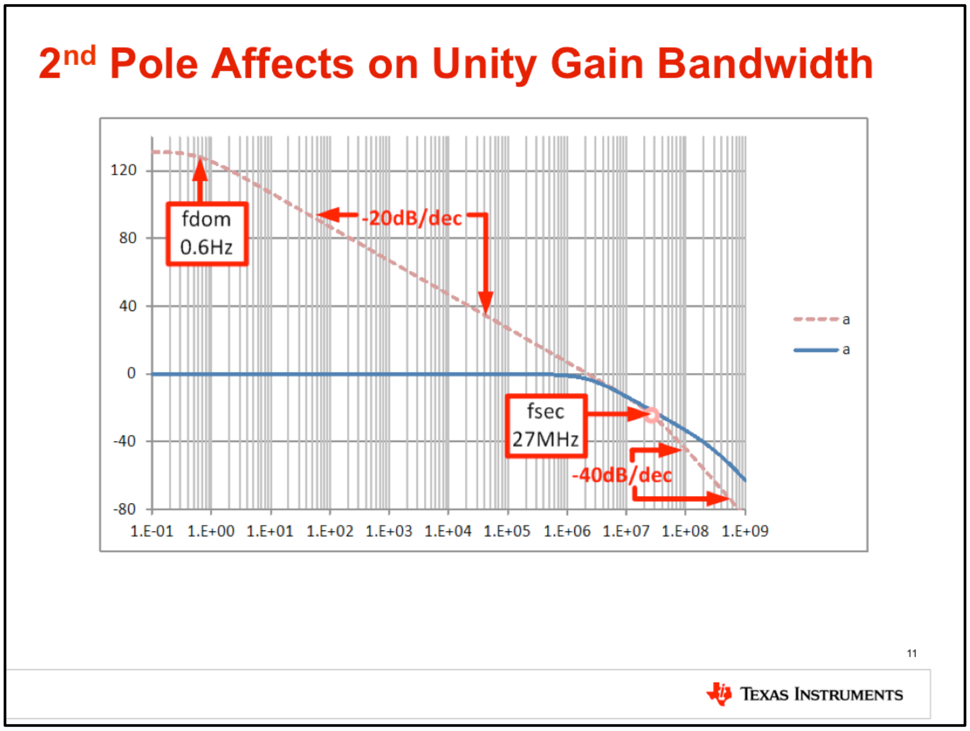
This slide depicts the Aol and phase curves for a simplified simulation model on the left. Notice that only the dominant pole appears in the Aol curve.

When we look at the corresponding phase plot, we see the corresponding 90 degrees of phase shift due to the dominate pole. At higher frequencies there is clearly no additional pole since the phase plot remains constant. Recall that phase starts to change 1 decade prior to the pole frequency.

On the right we see the Aol and phase curves for a more comprehensive 2-pole simulation model. Again we see the presence of the dominant pole at low frequency. Looking at the phase plot we see a shift, which indicates the presence of a high-frequency pole. Notice that even though the pole is located beyond the unity gain bandwidth, it still affects the phase within the bandwidth of the device.



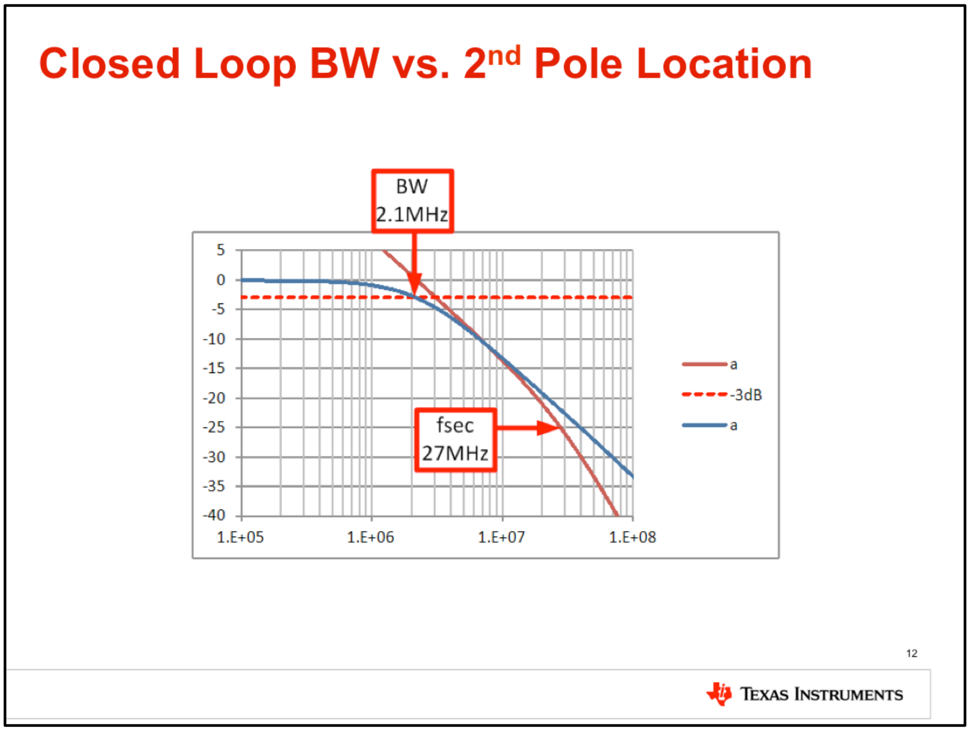
The second pole in the AOL curve will affect the magnitude and phase of the op amps closed loop response. In fact, the closed loop response of an amplifier with two or more poles in the AOL curve is given by this transfer function, where s is j x omega, omega-n is the natural frequency, and zeta is the damping factor. The log magnitude graph of the second order system shows the gain in dB vs. frequency for different values of zeta. Notice that for some values of zeta the gain increases greatly near the natural frequency. This dramatic increase is called gain peaking. Zeta is related to the positioning of the second pole. When the second pole is at very high frequencies relative to the unity gain frequency, the value of zeta is large and there is effectively no gain peaking. However, if the second pole is close to the unity gain frequency, the value of zeta is small and peaking can be significant. Gain peaking occurs with real world op amps and is modeled in most op amp macro models. Gain peaking will introduce errors for frequencies near the natural frequency and will affect the bandwidth.



Here we have a plot of the open loop gain of an amplifier and the closed loop gain of a buffer. The open loop gain curve is shown by the red dotted line while the closed loop gain is the solid blue line. The dominant pole in the Aol curve is located at 0.6Hz. At frequencies greater than 0.6Hz, the Aol curve rolls off at a rate of -20dB per decade until is crosses unity gain, or 0dB which is approximately 2MHz. Notice that the closed loop gain starts to follow the Aol curve once loop gain runs out.

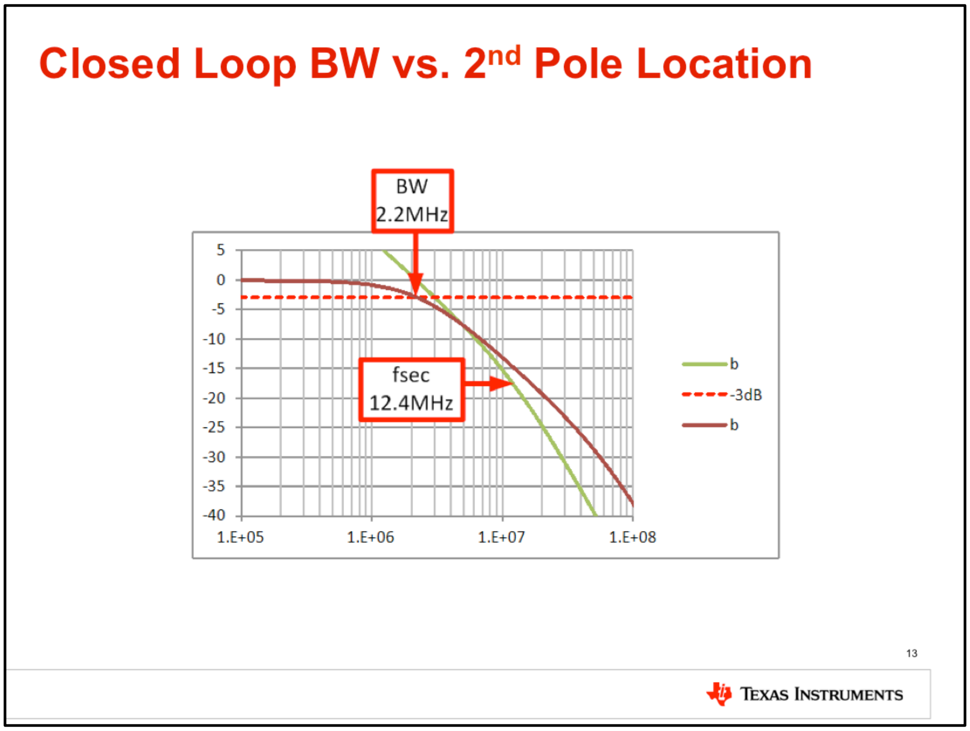
This plot also shows the presence of a second, high-frequency pole located at 27MHz. Above this frequency the Aol curve decreases at a rate of 40dB per decade.

The location of the second pole will affect the bandwidth of the circuit. We will find that as the frequency of the pole decreases, the bandwidth will increase and vice versa.



Now let's zoom in on the high-frequency portion of the graph. When the second pole is located at 27MHz we find the bandwidth, or -3dB point, is 2.1MHz.

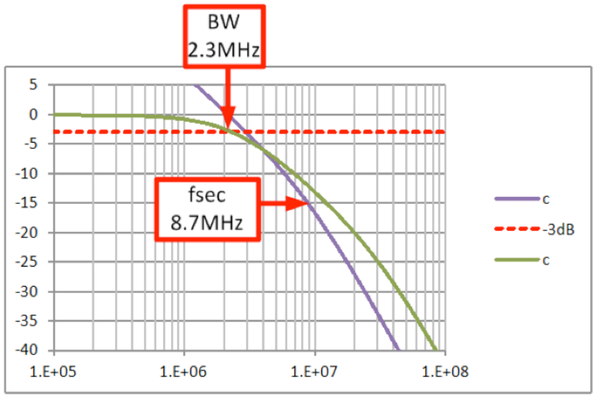
In the next few slides we will decrease the frequency of the second pole location from 27MHz down to 2.5MHz.



Here the second pole frequency was reduced from 27MHz to 12.4MHz and the bandwidth increased from 2.1MHz to 2.2MHz.

Now I will flip through the slides quickly. Notice the bandwidth increases as the second pole frequency decreases.

Closed Loop BW vs. 2nd Pole Location



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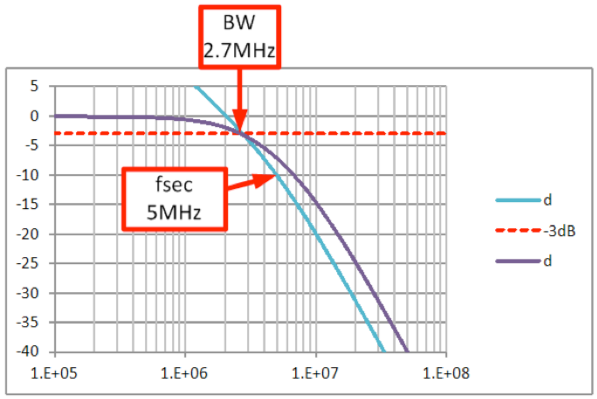
[pause 2 seconds]

Closed Loop BW vs. 2nd Pole Location



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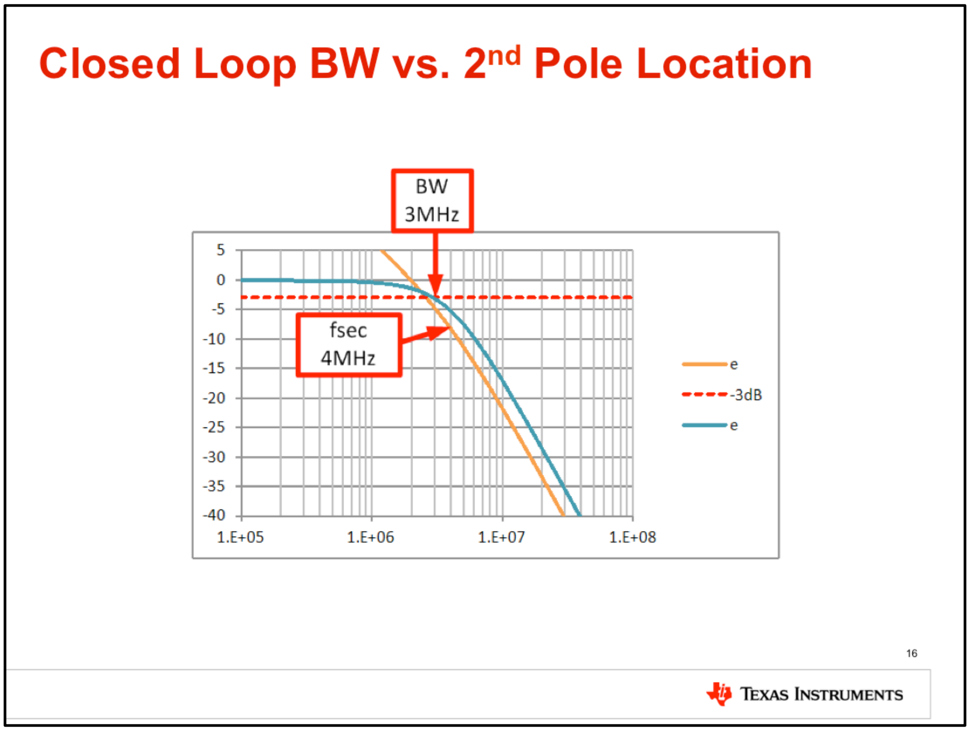
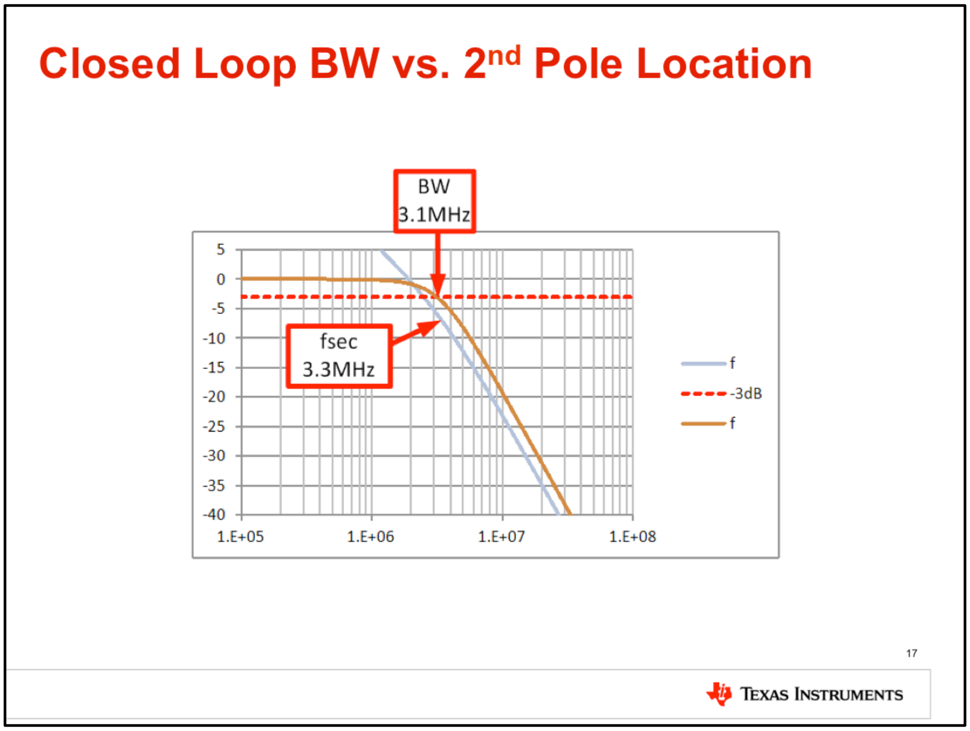
TEXAS INSTRUMENTS

[pause 2 seconds]

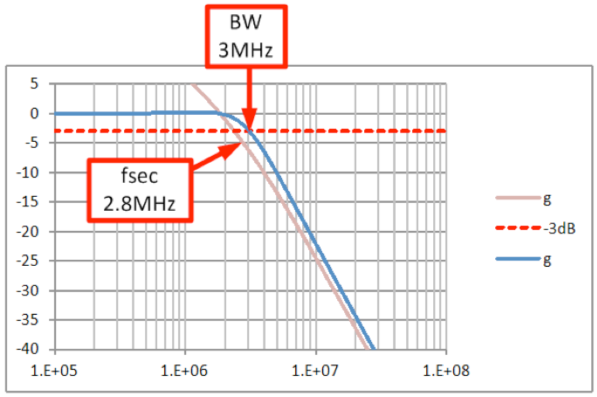


[pause 2 seconds]



[pause 2 seconds]

Closed Loop BW vs. 2nd Pole Location



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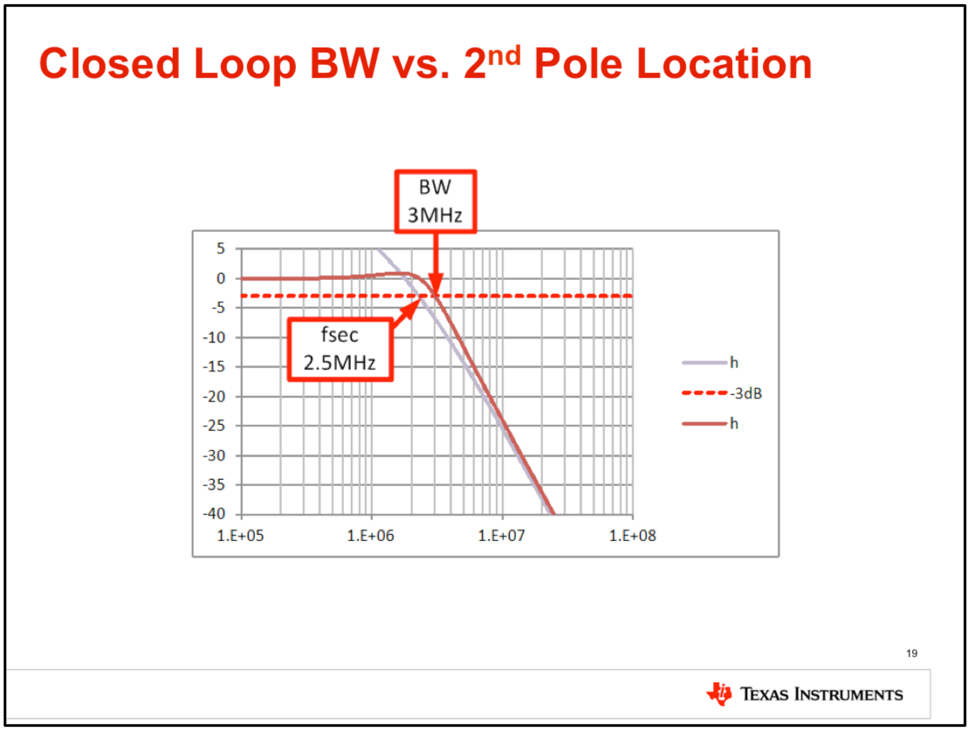
[pause 2 seconds]



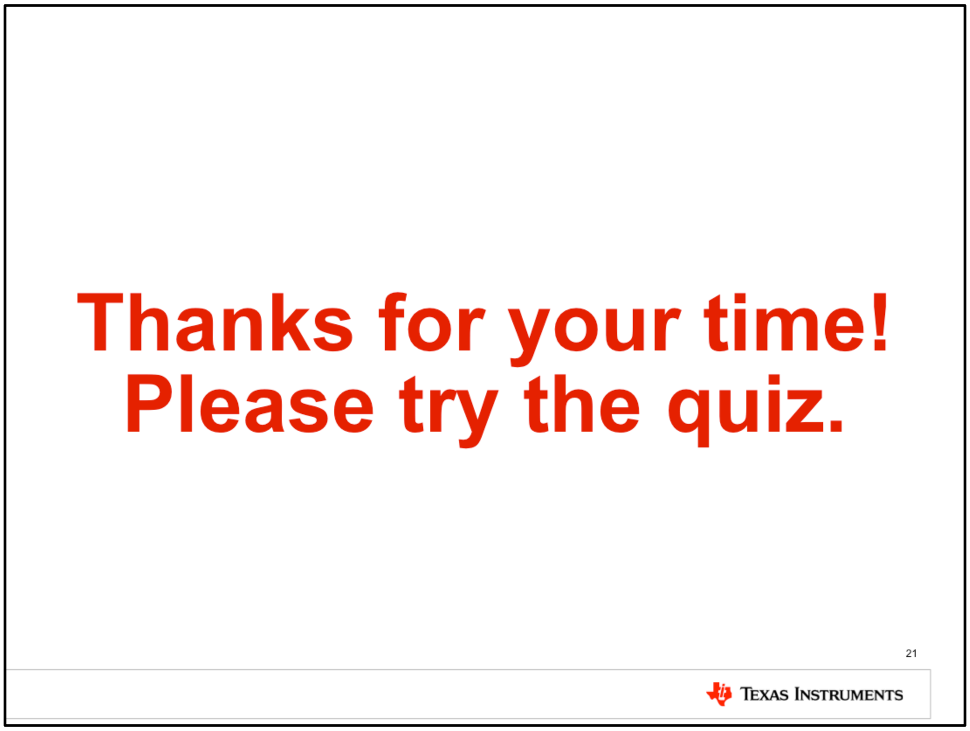
Finally, when the second pole is near the unity gain bandwidth, the closed-loop bandwidth stops changing and we see significant gain peaking.

Closed Loop BW vs. 2nd Pole Location

Second Pole f_{SEC} (MHz)	Bandwidth BW (MHz)	Gain Peaking
27	2.1	0dB
12.4	2.2	0dB
8.7	2.3	0dB
5.0	2.7	0dB
4.0	3.0	0dB
3.3	3.1	0dB
2.8	3.0	0.2dB
2.5	3.0	1.0dB

Unity Gain Bandwidth = 2MHz

This table summarizes the effect of the second pole's location verses peaking and closed loop bandwidth. It is worth noting that the peaking effect will only happen for low gains. In later videos we will cover the subject of stability and show more details on the concept of gain peaking. For now it is important to be aware that gain peaking can occur in amplifiers with second poles in their Aol. Furthermore, this effect is normally included in SPICE op amp macro models. Finally, the magnitude of the peaking should generally be less than a few decibels and the change in bandwidth should be less than a factor of two.



In summary, this video discussed why you should always use the non-inverting gain to calculate bandwidth and secondary effects (namely high-frequency pole location) on bandwidth.

Thank you for time! Please try the quiz to check your understanding of this video's content.

Bandwidth 3

Multiple Choice Quiz

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Quiz: Bandwidth 3

1. What is a dominant pole?

a. A high frequency pole that affects closed loop bandwidth.
b. A high frequency pole that causes gain peaking.
c. The low frequency pole in the Aol curve.
d. An external pole added to attenuate gain.

2. What is dc open loop gain?

a. The open loop gain at low frequencies.
b. The open loop gain at unity gain.
c. The high frequency open loop gain.
d. There is no parameter called dc open loop gain.

3. Under what circumstances would gain bandwidth product only be defined for a range of gains? For example, gain bandwidth is only defined for closed loop gain greater than 50.

a. The gain bandwidth is only defined for low bandwidth amplifiers
b. The gain bandwidth is only defined for voltage feedback amplifiers
c. The gain bandwidth is only defined if the Aol slope is -40dB/decade
d. The gain bandwidth is only defined if the Aol slope is -20dB/decade

Quiz: Bandwidth 3

4. An inverting amplifier has a gain of -1 and the op amp's gain bandwidth product is 22MHz. What is the closed loop bandwidth?

a. 22MHz
b. 11MHz
c. 2.2MHz
d. 1MHz

5. A non-inverting amplifier has a gain of +1 and the op amp's gain bandwidth product is 22MHz. What is the closed loop bandwidth?

a. 22MHz
b. 11MHz
c. 2.2MHz
d. 1MHz

Quiz: Bandwidth 3

6. What effect does a second pole in the AoI curve have on closed loop response?

a. Depending on the position of the second pole, the closed loop response can have gain peaking.
b. Depending on the position of the second pole, the closed loop bandwidth can be different than predicted by the gain bandwidth product.
c. A second pole will increase the slew rate for the amplifier.
d. A second pole will cancel the phase shift of the first pole.
e. Options 1 and 2 are correct
f. Options 3 and 4 are correct

Bandwidth 3

Multiple Choice Quiz: Solutions

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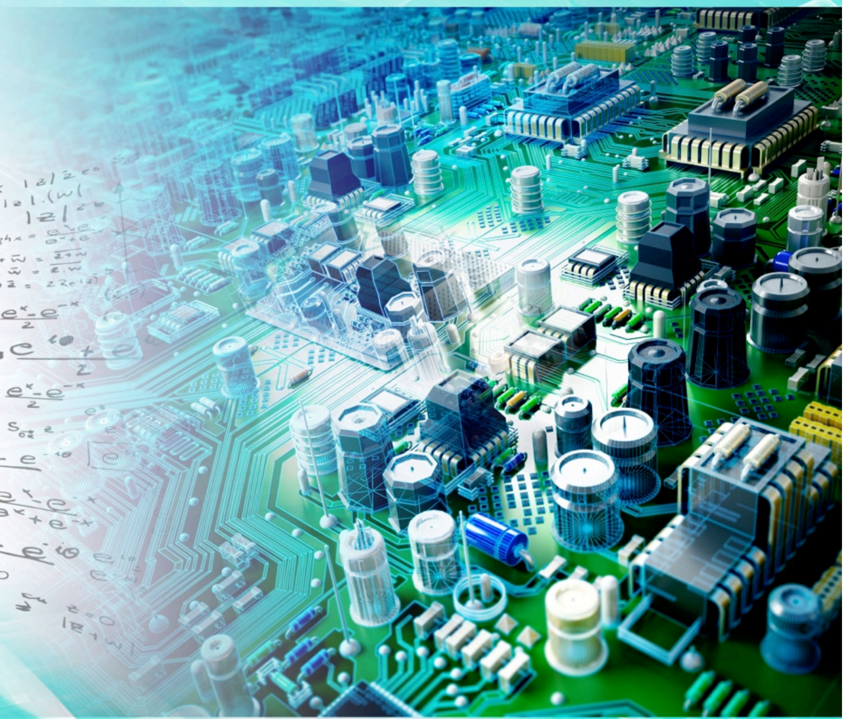

Quiz: Bandwidth 3

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Quiz: Bandwidth 3

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Bandwidth 3

Exercises

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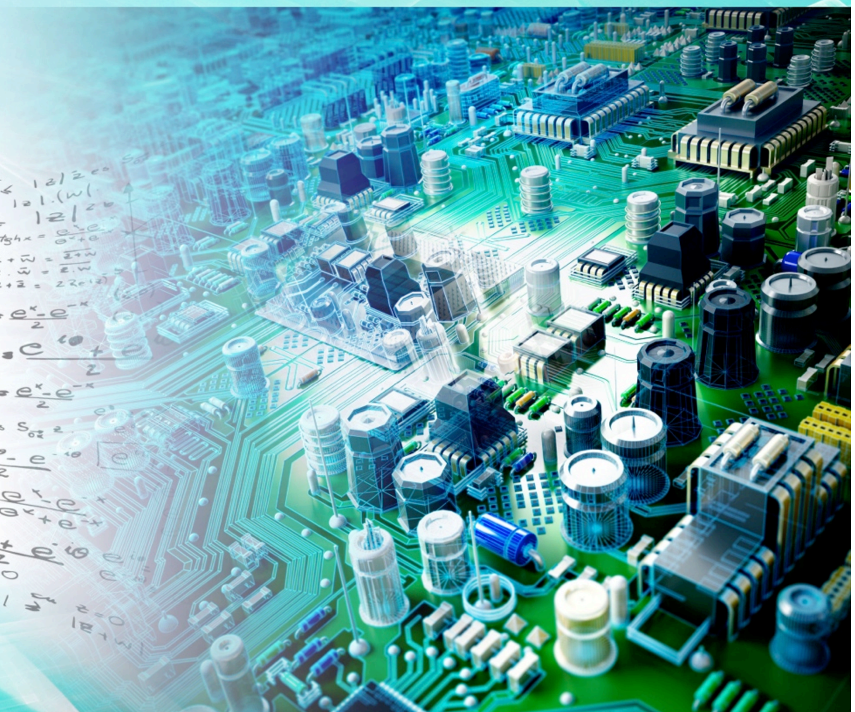


1. Using the table below, calculate the dominant pole in the Aol curve.

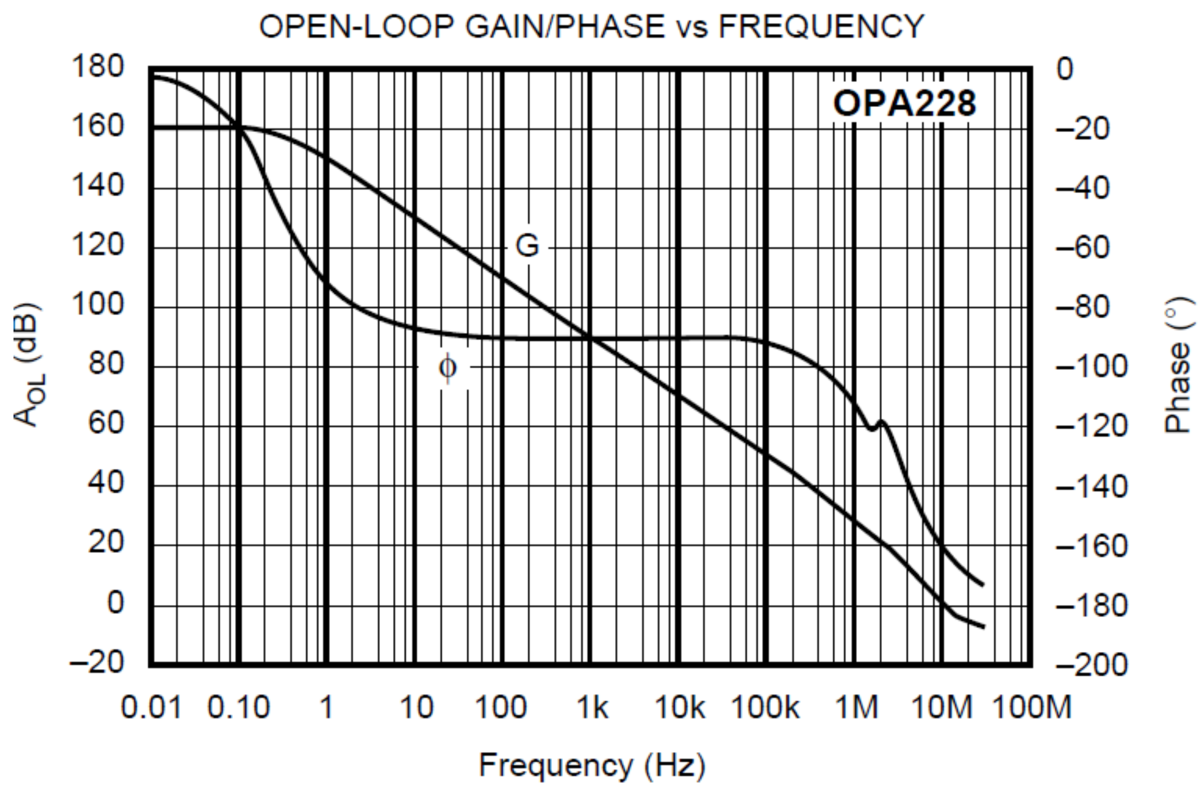
ELECTRICAL CHARACTERISTICS: V_S = 2.7V to 5.5V

Boldface limits apply over the temperature range, **T_A = −40°C to +85°C**. V_S = 5V.

All specifications at T_A = +25°C, R_L = 1kΩ connected to V_S/2 and V_{OUT} = V_S/2, unless otherwise noted.

PARAMETER		TEST CONDITIONS	OPA350, OPA2350, OPA4350 MIN	TYP(1)	MAX	UNIT
OPEN-LOOP GAIN						
Open-Loop Voltage Gain	A_{OL}	R_L = 10kΩ, 50mV < V_O < (V+) −50mV	100	122		dB
T_A = −40°C to +85°C		**R_L = 10kΩ, 50mV < V_O < (V+) −50mV**	**100**			dB
		R_L = 1kΩ, 200mV < V_O < (V+) −200mV	100	120		dB
T_A = −40°C to +85°C		**R_L = 1kΩ, 200mV < V_O < (V+) −200mV**	**100**			dB
FREQUENCY RESPONSE		C_L = 100pF				
Gain-Bandwidth Product	GBW	G = 1		38		MHz
Slew Rate	SR	G = 1		22		V/μs
Settling Time: 0.1%		G = +1, 2V Step		0.22		μs

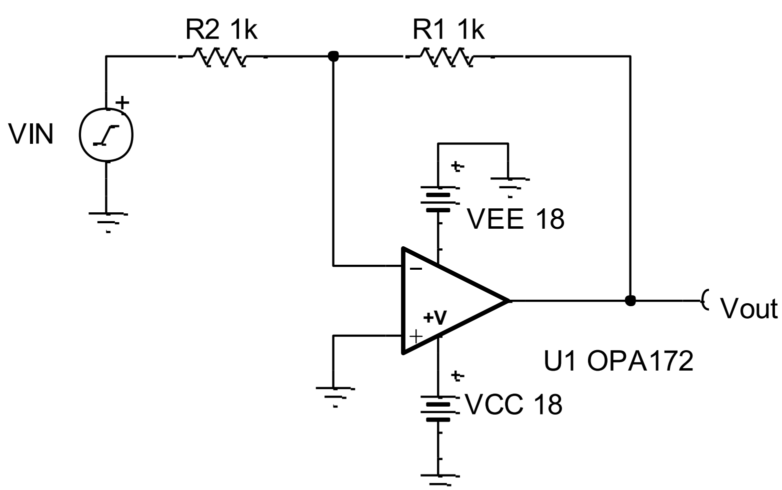
2. The data sheet for the OPA228 states that the amplifier can only be used for closed loop gain greater than 5V/V. Use the open loop gain curve below to explain



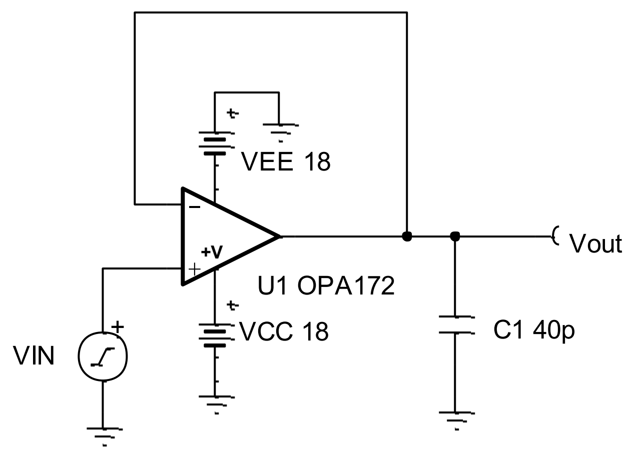
3. Find the closed loop bandwidth for the circuit below. Use the table from the data sheet below.

At T_A = +25°C, V_S = ±2.25 V to ±18 V, V_{CM} = V_{OUT} = $V_S/2$, and R_L = 10 kΩ connected to $V_S/2$, unless otherwise noted.

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
FREQUENCY RESPONSE						
GBP	Gain bandwidth product			10		MHz
SR	Slew rate	G = +1		10		V/μs
		To 0.1%, V_S = ±18 V, G = +1, 10-V step		2		μs



4. Simulate the ac transfer characteristic for the circuit below. How much gain peaking does it have and what is the closed loop bandwidth.



Bandwidth 3

Solutions

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1. Using the table below, calculate the dominant pole in the Aol curve.

ELECTRICAL CHARACTERISTICS: V_S = 2.7V to 5.5V

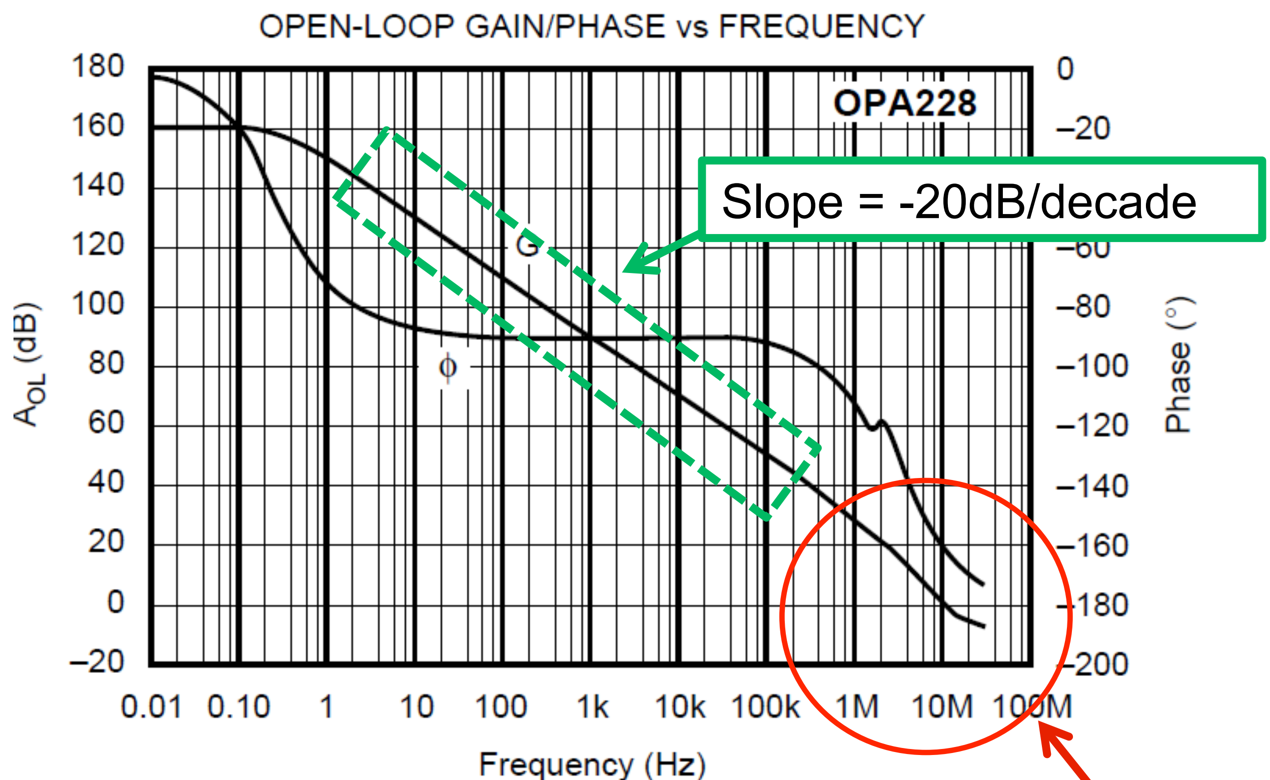
Boldface limits apply over the temperature range, **T_A = −40°C to +85°C**. V_S = 5V.

All specifications at T_A = +25°C, R_L = 1kΩ connected to $V_S/2$ and $V_{OUT} = V_S/2$, unless otherwise noted.

PARAMETER		TEST CONDITIONS	OPA350, OPA2350, OPA4350 MIN	TYP(1)	MAX	UNIT
OPEN-LOOP GAIN						
Open-Loop Voltage Gain	A_{OL}	R_L = 10kΩ, 50mV < V_O < (V+) −50mV	100	122		dB
T_A = −40°C to +85°C		**R_L = 10kΩ, 50mV < V_O < (V+) −50mV**	**100**			dB
		R_L = 1kΩ, 200mV < V_O < (V+) −200mV	100	120		dB
T_A = −40°C to +85°C		**R_L = 1kΩ, 200mV < V_O < (V+) −200mV**	**100**			dB
FREQUENCY RESPONSE		C_L = 100pF				
Gain-Bandwidth Product	GBW	G = 1		38		MHz
Slew Rate	SR	G = 1		22		V/µs
Settling Time: 0.1%		G = +1, 2V Step		0.22		µs

$$f_{dom} = \frac{38\text{MHz}}{10^{\frac{122}{20}}} = 30.184\ \text{Hz}$$

2. The data sheet for the OPA228 states that the amplifier can only be used for closed loop gain greater than 5V/V. Use the open loop gain curve below to explain

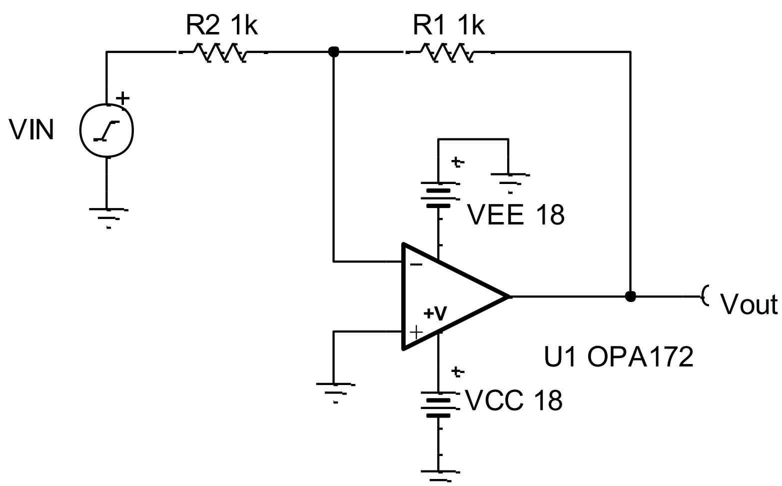


Slope ≠ -20dB/decade
A second pole in Aol causes the slope to change. Not stable for gain < 5V/V

3. Find the closed loop bandwidth for the circuit below. Use the table from the data sheet below.

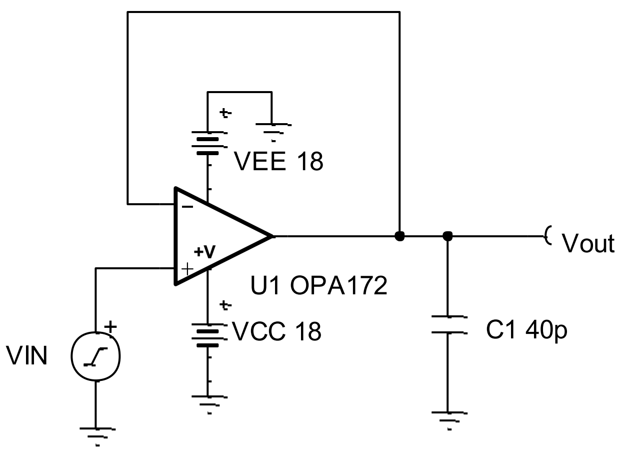
At T_A = +25°C, V_S = ±2.25 V to ±18 V, V_{CM} = V_{OUT} = $V_S/2$, and R_L = 10 kΩ connected to $V_S/2$, unless otherwise noted.

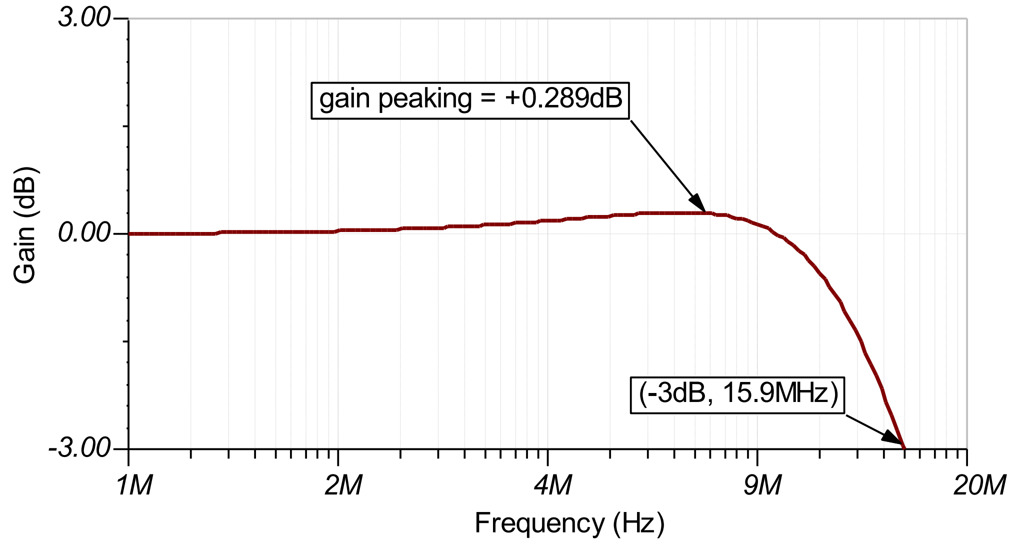
PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
FREQUENCY RESPONSE						
GBP	Gain bandwidth product			10		MHz
SR	Slew rate	G = +1		10		V/μs
		To 0.1%, V_O = ±18 V, G = +1, 10-V step		2		μs



$$f_c = \frac{GBP}{\frac{R_f}{R_1} + 1} = \frac{20MHz}{2} = 10MHz$$

4. Simulate the ac transfer characteristic for the circuit below. How much gain peaking does it have and what is the closed loop bandwidth.





1213 - Bandwidth 3 - exercise 4.TSC