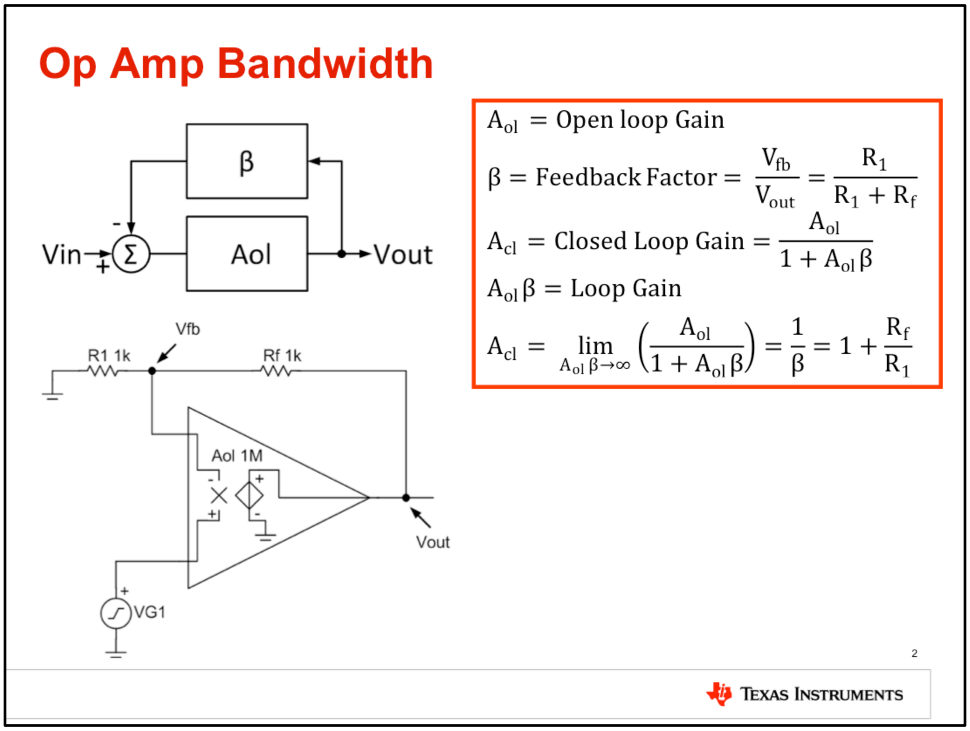
Hello, and welcome to the TI Precision Lab discussing op amp bandwidth, part 2.

In this video we'll discuss open and closed loop gain, gain bandwidth product, and quiescent current vs. bandwidth. We will also simulate the bandwidth of a circuit and show that it correlates to our calculated results.

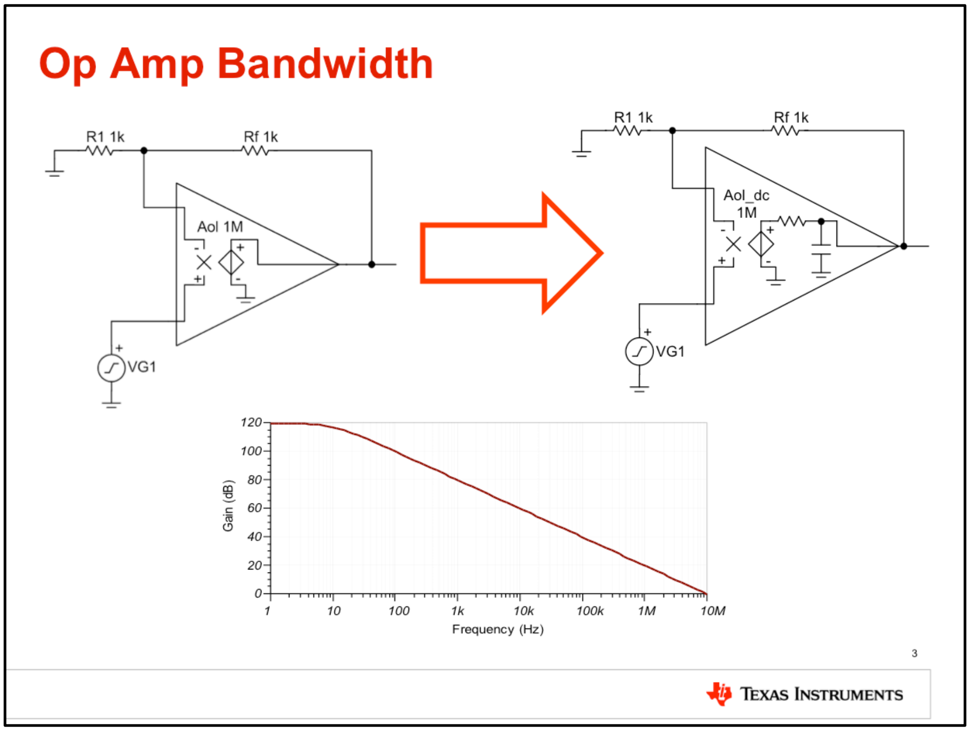


The open-loop gain, or Aol, of an op amp represents the gain applied by the amplifier to the voltage difference between the inputs of the device. Aol for an ideal amplifier is infinite. Modern real-world op amps, however, have open loop gains in excess of 1 million volts per volt, or 120dB.

In order for an amplifier to be useful, negative feedback is required. This is accomplished with Rf and R1. Sometimes this is referred to as 'closing the loop'. Rf and R1 represent the beta network, or feedback factor, of the op amp circuit. Beta is a measure of how much of the output voltage, Vout, is fed back to the inverting terminal of the op amp. In this circuit we see that Rf and R1 create a voltage divider. Therefore beta is equal to R1 divided by R1+Rf.

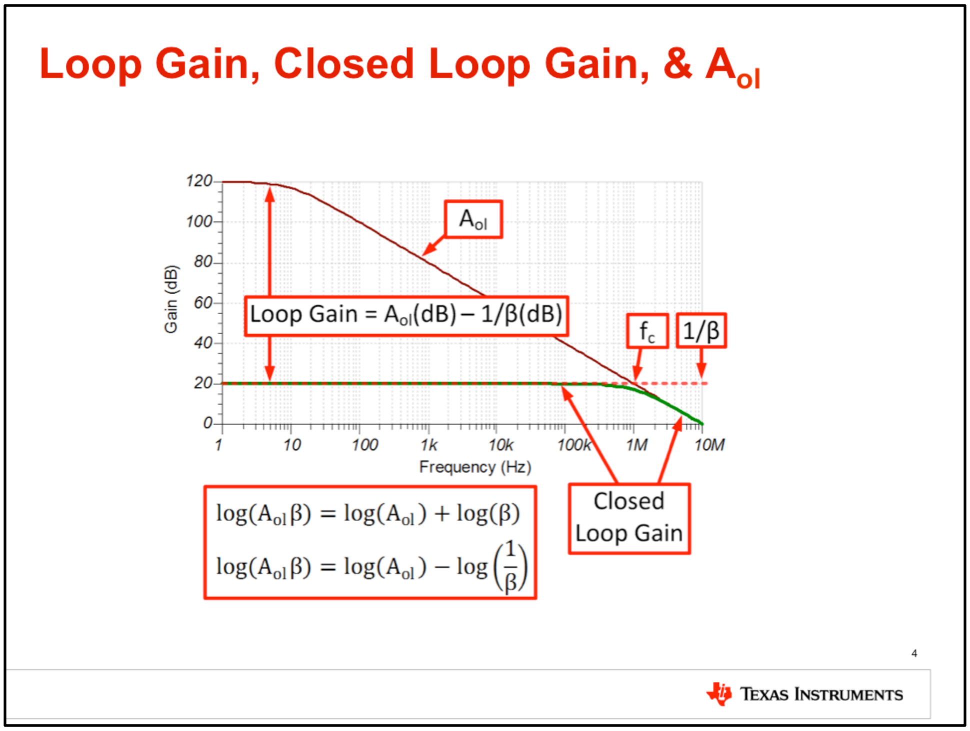
In addition to the open loop gain of the op amp, we now have what is called the 'closed-loop gain', or Acl, of the op amp circuit. The equation for Acl is Aol divided by 1 + Aol*Beta, where Aol*Beta is known as the 'Loop Gain'. This equation can be re-arranged as shown.

The close loop gain equation can be simplified for very large values of loop gain or Aol x β. Looking at the loop gain equation you can see that as Aol x β increases towards infinity, you can ignore the "1" term in the denominator. This leaves Aol over Aol x β, and the Aol terms will cancel, leaving only 1 over beta. Substituting the



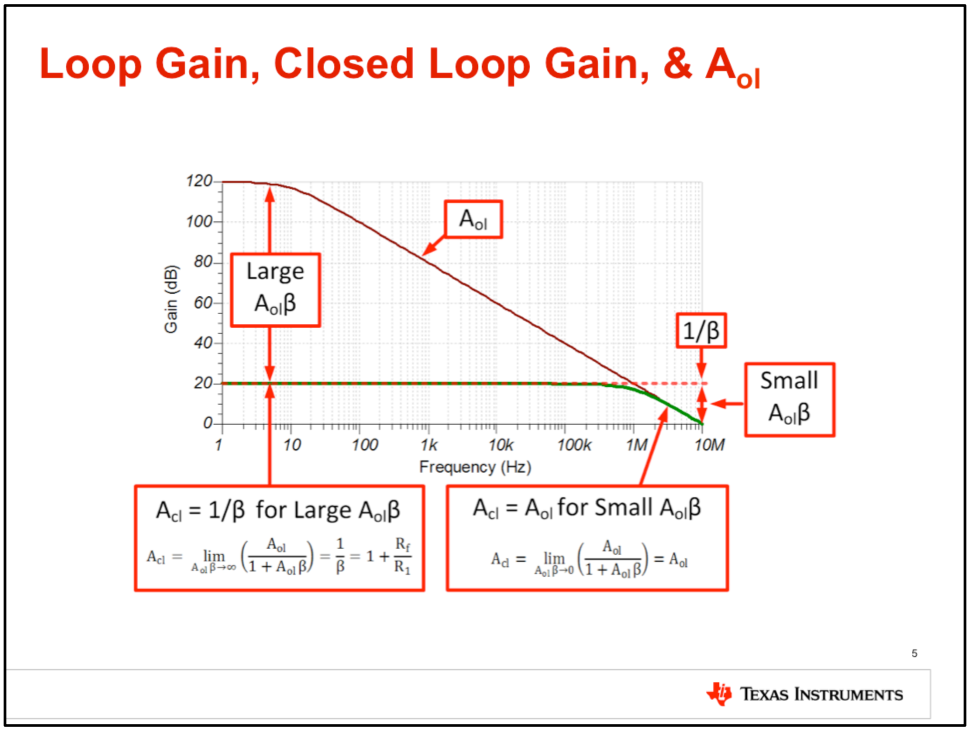
In the real-world, however, the open-loop gain of an op amp has a low-frequency, or dominate pole. This can be thought of as an RC filter as shown here.

This simulation depicts the open loop gain of a real-world op amp. At dc, or low frequencies, Aol is very large. In this case it is 120dB, or 1,000,000 V/V. As frequency increases, Aol decreases at a rate of ***-20dB/decade***. We see that at 10MHz, the open loop gain is 0dB, or 1V/V.



Now that we understand that the open loop gain decreases with frequency, how does that affect our closed-loop gain?

Recall that the term Aol*Beta is known as Loop Gain. If we plot the open loop and 1/β on a logarithmic axis, loop gain is the difference between the two curves. The mathematical proof that loop gain is Aol – 1/β on a logarithmic curve is given at the bottom of the slide. In this example, 1/β is shown as a horizontal dashed line at 20dB. Notice that closed loop gain follows 1/β for low frequencies, but follows the Aol curve for high frequencies. Also notice that the point at which the 1/β curve intersects the Aol curve is the closed loop bandwidth. Let's take a deeper look at the reasons why closed loop gain follows 1/β for low frequencies and follows Aol at higher frequencies.



At low frequencies, loop gain, or Aol*β is large. Remember that closed loop gain is Aol divided by 1+Aol*β , so for large values of Aol*β, you can ignore the "1" term. This leaves Aol over Aol*β, and the Aol terms will cancel. Thus, the closed loop gain for large values of Aol*β is approximately equal to 1/β. In this case, 1/β is the familiar gain equation of a non-inverting amplifier, 1+Rf/R1.

At high frequencies, Aol*β is small. Remember that closed loop gain is Aol divided by 1+Aol*β , so for small values of Aol*β, you can ignore the "Aol*β" term. This leaves Aol over 1, or just Aol. Thus, the closed loop gain follows the Aol curve for small values of Aol*β.

We define the bandwidth of the circuit as the frequency at which the 1/β and Aol curves intersect. So, given the Aol curve from an op amp data sheet you can approximate the bandwidth of your circuit for the desired closed loop gain.

However, notice that the x-axis is logarithmic. Therefore, graphically determining the bandwidth can be inaccurate.

Gain Bandwidth Product

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

$GBW = Gain \cdot BW$

In this example, for any gain from 0dB to Avol.

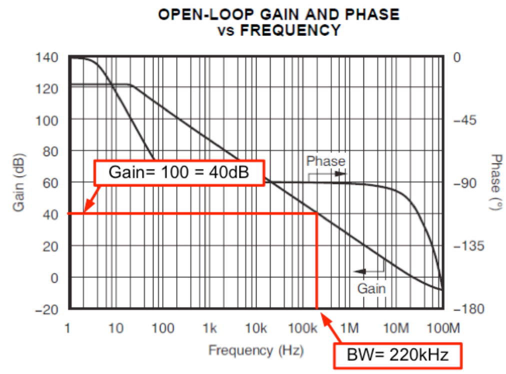
where
GBW -- Gain Bandwidth in Hz
Gain -- closed loop voltage gain
BW -- Bandwidth in Hz

For example

$Gain = 100$

Closed Loop Bandwidth is calculated:

$$BW = \frac{GBW}{Gain} = \frac{22MHz}{100} = 220kHz$$



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TEXAS INSTRUMENTS

Another approach to determining bandwidth is to use the gain-bandwidth product specification from an op amp data sheet.

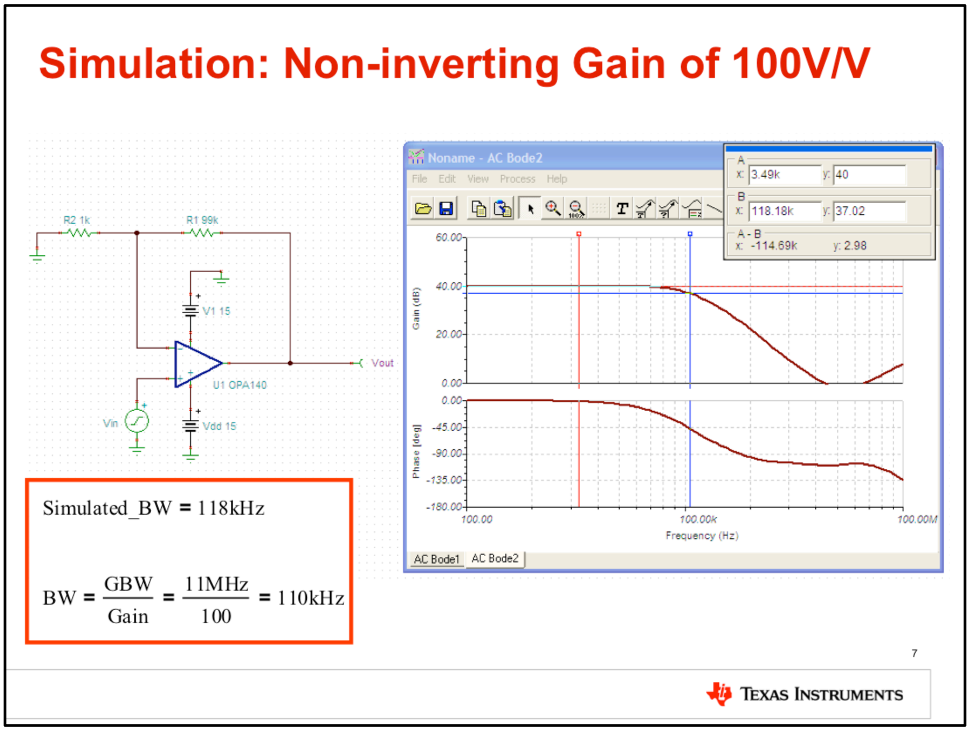
The gain bandwidth product is literally the product of the linear gain and the bandwidth. Therefore, you can solve for one of the variables given the other two.

For example, let's calculate the bandwidth of a circuit that uses the OPA827 in a gain of 100V/V.

From the data sheet we see that the gain bandwidth product is 22MHz.

Solving the gain bandwidth equation for bandwidth tells us that the bandwidth is the gain bandwidth product divided by the linear gain. Dividing the OPA827 gain bandwidth product of 22MHz by the circuit gain of 100V/V yields a bandwidth of 220kHz.

This calculation is verified by looking at the OPA827 open loop gain curve from the data sheet. If we draw a horizontal line at the closed loop gain of 100V/V, or 40dB, until it intersects Aol we find the corresponding bandwidth is approximately 200kHz. Notice that solved graphically you may incorrectly interpret the bandwidth to be 200kHz, though by calculation we found it to be 220kHz.



Now let's compare a calculation to a TINA-TI simulation.

Here we have an OPA140 in a non-inverting amplifier configuration with a closed-loop gain of 100V/V, or 40dB.

The OPA140 has a gain bandwidth product of 11MHz. Given that our closed loop gain is 100V/V we find that the calculated bandwidth is 110kHz.

Here we simulate the closed-loop bandwidth of the given circuit. At the -3dB point, or 37dB, the simulated bandwidth is 118kHz.

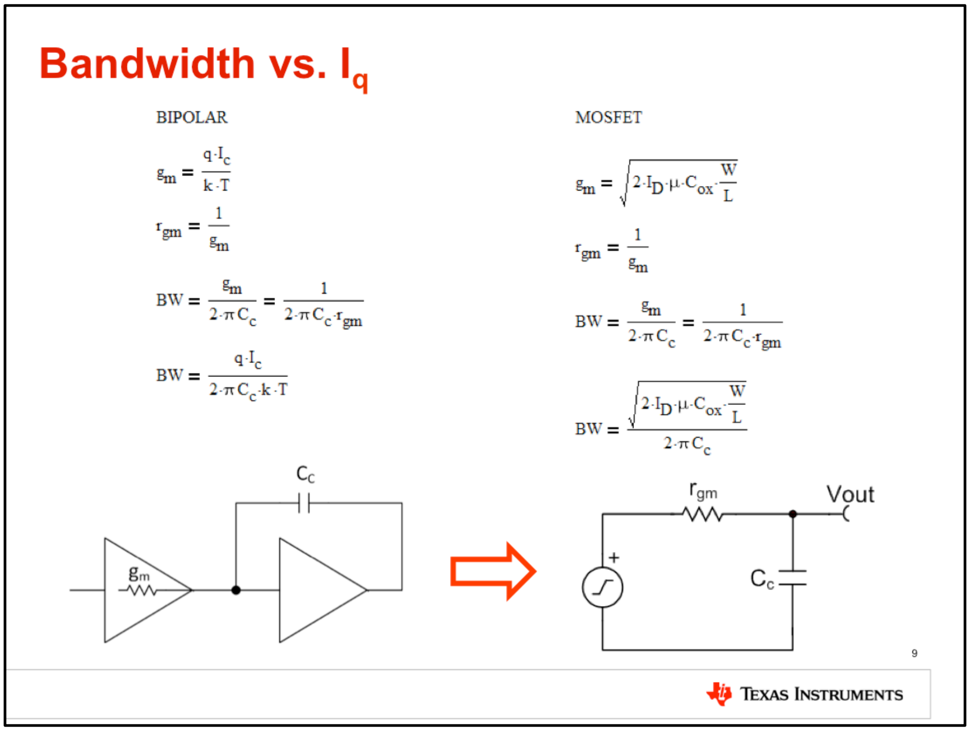
Though not exact, we have correlation between our calculated and simulated results.

Bandwidth vs. I_q

Op Amp	Typical GBW	Typical Iq
OPA369	12kHz	0.8uA
OPA333	350kHz	17uA
OPA277	1MHz	790uA
OPA129	1MHz	1.2mA
OPA827	22MHz	4.8mA
OPA350	38MHz	5.2mA
OPA211	45MHz (Gain=1)	3.6mA
OPA835	51MHz (Gain=1)	250uA
OPA847	600MHz (Gain=12)	18.1mA

Finally, let's look at a number of op amps that depict a range of gain bandwidth products and their corresponding quiescent current, Iq.

In the slide we list Gain Bandwidth Products for different amplifiers that range from 12kHz to 600MHz. The OPA369, for example, is a very low bandwidth amplifier. This device is designed specifically to have very a low quiescent current of 0.8uA and is called a micro-power device. It is more common for amplifiers have bandwidth in the range of 1MHz like the OPA277. Some amplifiers like the OPA350 and OPA211 have wider bandwidth to facilitate driving A/D converters and for other wide bandwidth applications. For very high speed applications amplifiers like the OPA835 and OPA847 can be used. In general, the wider bandwidth op amps require more quiescent current. However, there are some exceptions , as displayed by the OPA835.

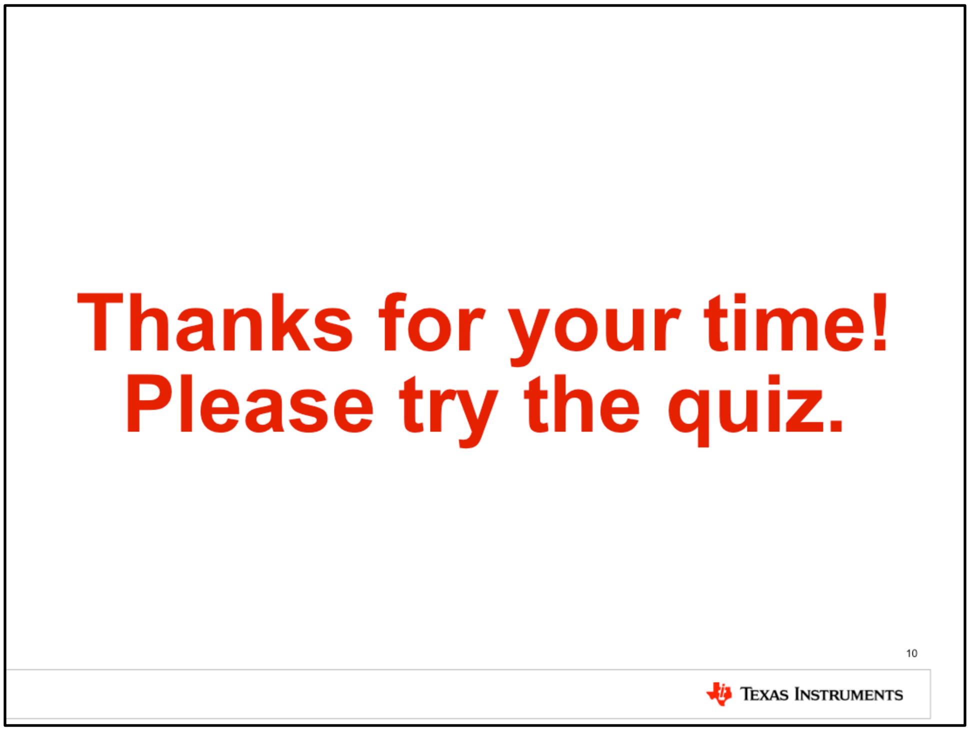


So, why are bandwidth and quiescent current directly related? Let's take a look at the physics relationships for both bipolar and CMOS transistors. Please note that it is not critical to get a deep understanding of transistor theory to understand amplifier bandwidth. The point here is to show that there are underlying physics principles that relate amplifier bandwidth to Iq.

If we look at the transconductance, or current gain, of a bipolar transistor and a MOSFET, we see that it is directly related to the collector and drain currents, respectively.

Inverting the transconductance yields the impedance, or r_{gm}. r_{gm} is the dynamic output impedance of the first stage inside the op amp. This output impedance drives the miller capacitance C_C. The series combination of r_{gm} and C_C form a low pass filter. This low pass filter is the dominant pole inside the amplifier that sets the bandwidth. In fact, you can see the third equation down is just another form of the traditional RC bandwidth equation BW = 1/(2*pi*RC). In the final equation, we substitute the original gm equation to show how bandwidth is related to gm. This relationship shows that increasing current consumption directly increases the BW of the bipolar op amp.

For a MOSFET, however, the bandwidth will increase proportionately to the square



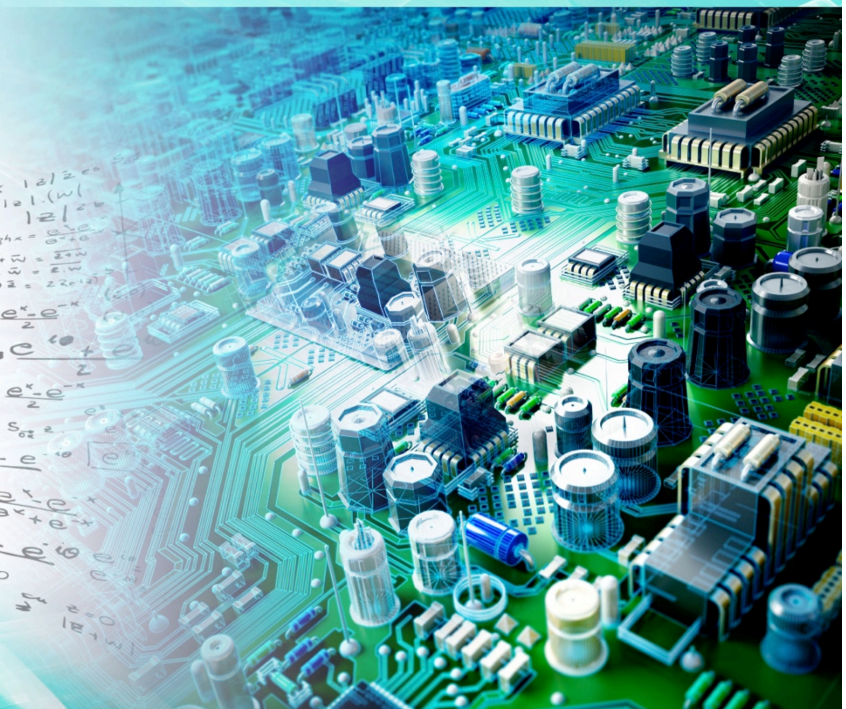
In summary, this video discussed open and closed loop gain, gain bandwidth product, and quiescent current vs. bandwidth. We also simulated the bandwidth of a circuit and showed that it correlated to our calculated results.

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

Bandwidth 2

Multiple Choice Quiz

TI Precision Labs – Op Amps



Quiz: Bandwidth 2

1. What happens to A_{OL} value below the dominant pole?

a. A_{OL} decreases by 20 dB/decade
b. A_{OL} decreases by 40 dB/decade
c. A_{OL} increases by 20 dB/decade
d. A_{OL} is the constant dc value

2. What happens to A_{OL} value above the dominant pole?

a. A_{OL} decreases by 20 dB/decade
b. A_{OL} decreases by 40 dB/decade
c. A_{OL} increases by 20 dB/decade
d. A_{OL} is the constant dc value

3. Why does closed loop gain follow the Aol curve at high frequencies?

a. Because loop gain is small
b. Because loop gain is large

Quiz: Bandwidth 2

4. If the gain bandwidth product for an amplifier is 1MHz, and the closed loop gain is 10, what is the bandwidth?

a. 1MHz
b. 10MHz
c. 100kHz
d. 10kHz

5. Amplifiers with high bandwidth tend to have ____ quiescent current than amplifiers with low bandwidth?

a. Higher
b. Lower

6. Compare a CMOS to a Bipolar amplifier. Assume both amplifiers have the same quisient current. Which will have the highest bandwidth?

a. CMOS
b. Bipolar

Quiz: Bandwidth 2

7. Looking at a wide range of different types of op amps, what is the range of bandwidth you would expect to see?

a. 100Hz to 1MHz
b. 100kHz to 1GHz
c. 100MHz to 10GHz
d. 10kHz to 500MHz

Bandwidth 2

Multiple Choice Quiz: Solutions

TI Precision Labs – Op Amps

Quiz: Bandwidth 2

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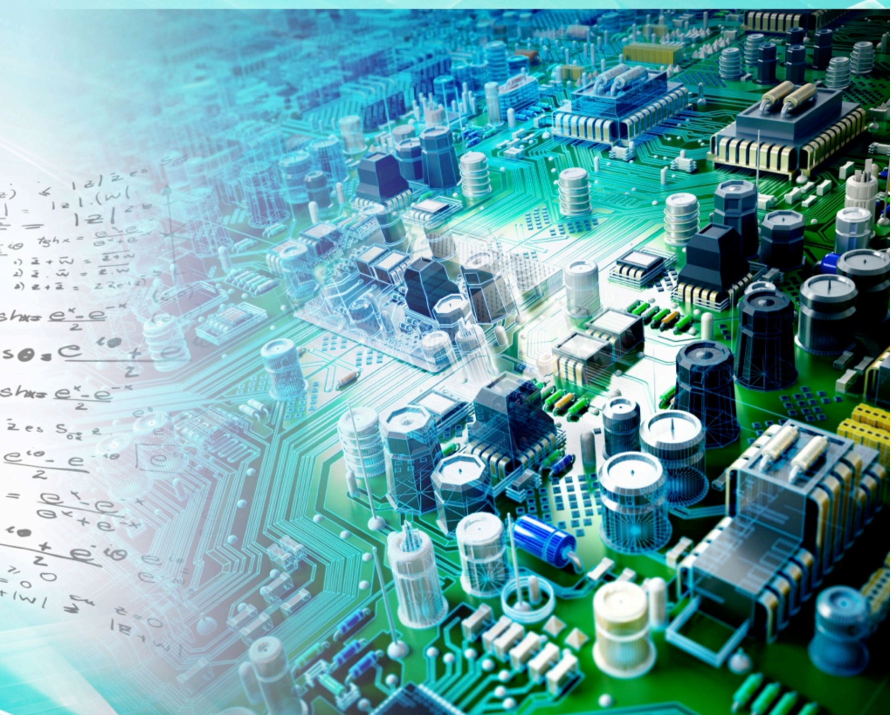
Bandwidth 2

Exercises

TI Precision Labs – Op Amps

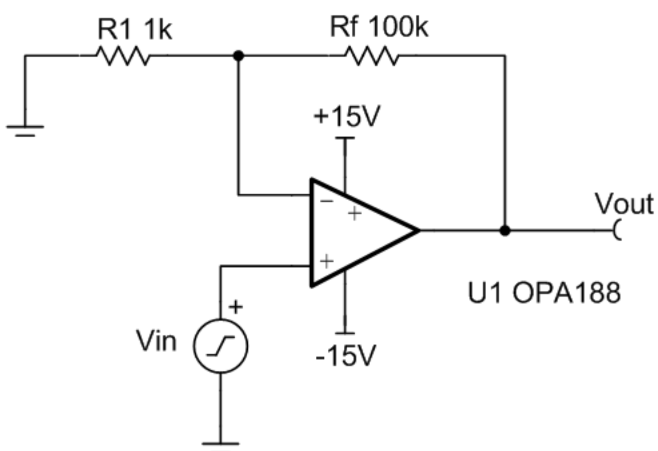


1. Find the closed loop bandwidth using the information given below.

ELECTRICAL CHARACTERISTICS:
Low-Voltage Operation, V_S = ±2 V to < ±4 V (V_S = +4 V to < +8 V)

At T_A = +25°C, R_L = 10 kΩ connected to V_S / 2[(1)], and V_{CM} = V_{OUT} = V_S / 2[(1)], unless otherwise noted.

PARAMETER		CONDITIONS	MIN	TYP	MAX	UNIT
FREQUENCY RESPONSE						
GBW	Gain-bandwidth product			2		MHz
SR	Slew rate	G = +1		0.8		V/μs
t_{OR}	Overload recovery time	V_{IN} × G = V_S		1		μs
THD+N	Total harmonic distortion + noise	1 kHz, G = 1, V_{OUT} = 1 Vrms		0.0001%		



2. Graphically determine the bandwidth using the Aol graph below.

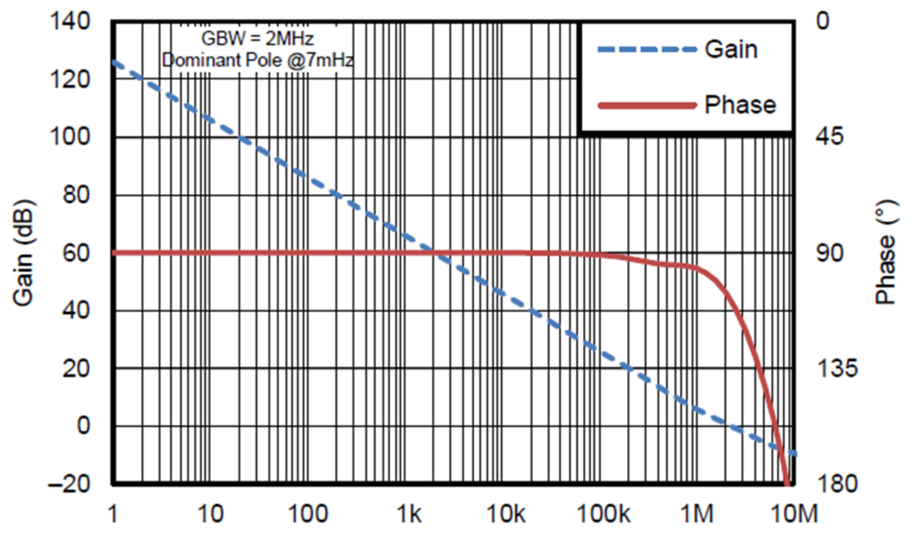
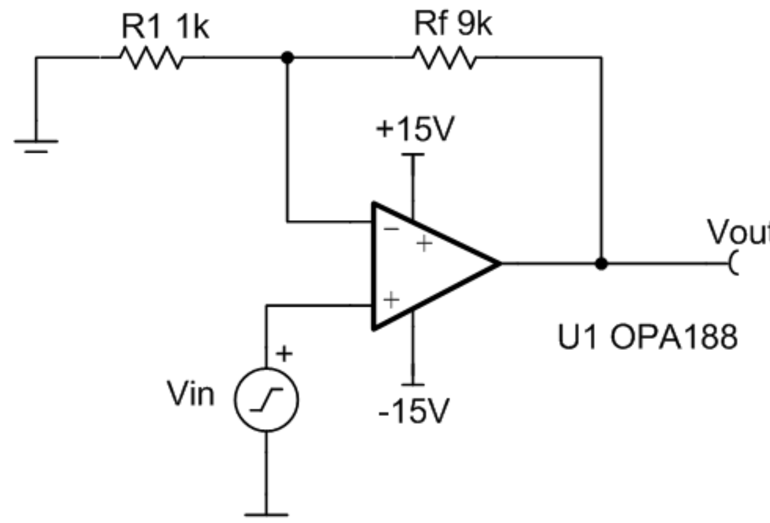


Figure 8. OPEN-LOOP GAIN AND PHASE vs FREQUENCY

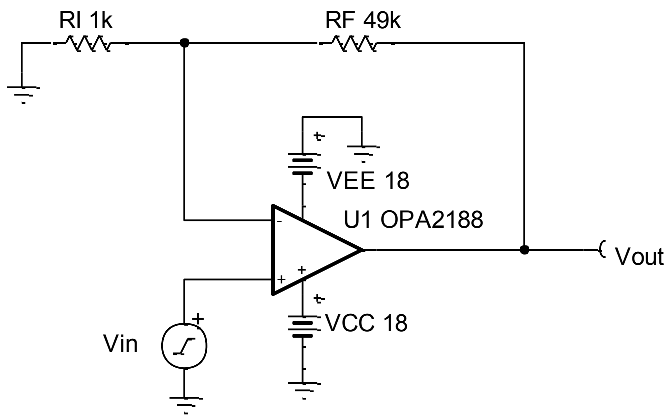


3. Simulate the circuit below to determine the bandwidth. Check simulation with hand calculations.

ELECTRICAL CHARACTERISTICS:
Low-Voltage Operation, $V_S = \pm 2$ V to < ±4 V ($V_S = +4$ V to < +8 V)

At $T_A = +25°C$, $R_L = 10\ k\Omega$ connected to $V_S / 2$(1), and $V_{CM} = V_{OUT} = V_S / 2$(1), unless otherwise noted.

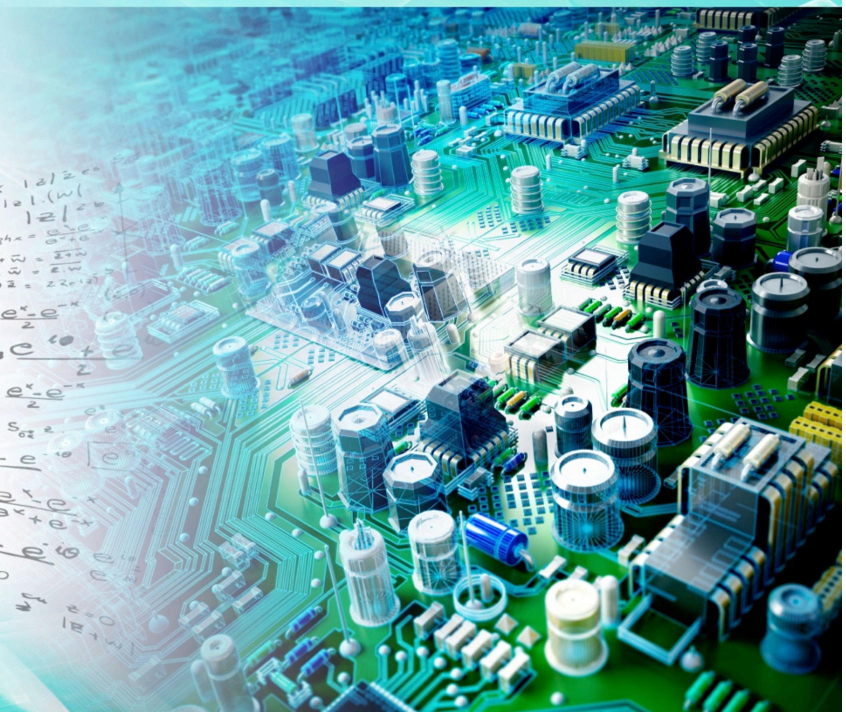
PARAMETER		CONDITIONS	MIN	TYP	MAX	UNIT
FREQUENCY RESPONSE						
GBW	Gain-bandwidth product			2		MHz
SR	Slew rate	G = +1		0.8		V/µs
t_{OR}	Overload recovery time	$V_{IN} \times G = V_S$		1		µs



Bandwidth 2

Solutions

TI Precision Labs – Op Amps



Texas Instruments

1. Find the closed loop bandwidth using the information given below.

ELECTRICAL CHARACTERISTICS:
Low-Voltage Operation, V_S = ±2 V to < ±4 V (V_S = +4 V to < +8 V)

At T_A = +25°C, R_L = 10 kΩ connected to V_S / 2[1], and V_{CM} = V_{OUT} = V_S / 2[1], unless otherwise noted.

PARAMETER		CONDITIONS	MIN	TYP	MAX	UNIT
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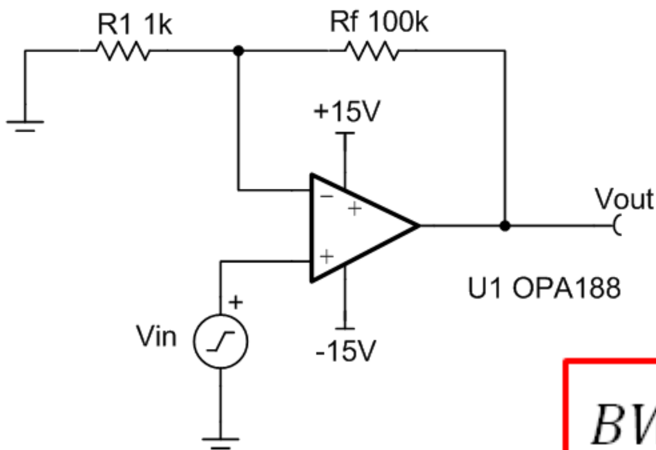
GBW	Gain-bandwidth product			2		MHz
SR	Slew rate	G = +1		0.8		V/µs
t_{OR}	Overload recovery time	V_{IN} × G = V_S		1		µs
THD+N	Total harmonic distortion + noise	1 kHz, G = 1, V_{OUT} = 1 Vrms		0.0001%		



$$BW_{cl} = \frac{GBW}{Gain} = \frac{2MHz}{1+\frac{Rf}{R1}} = \frac{2MHz}{101} = 19.8kHz$$

2. Graphically determine the bandwidth using the AoI graph below.

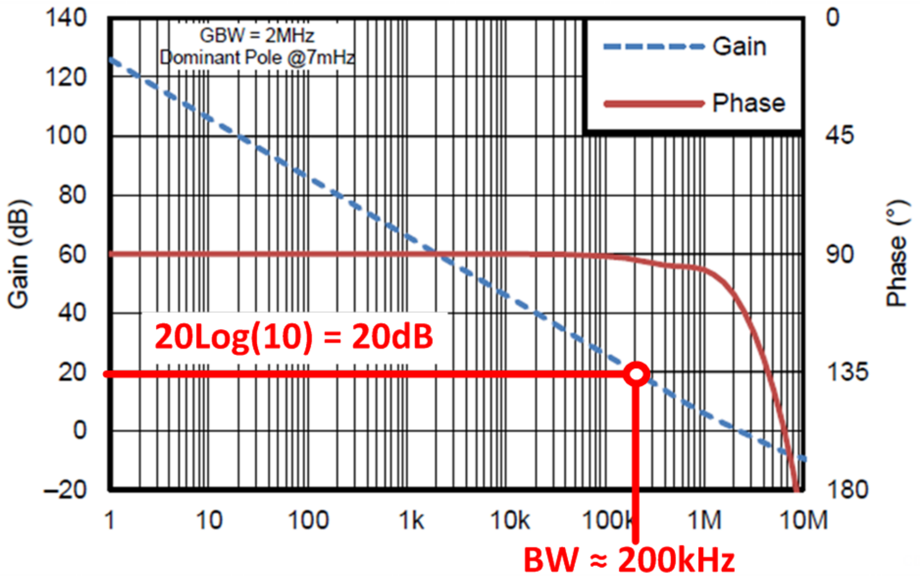
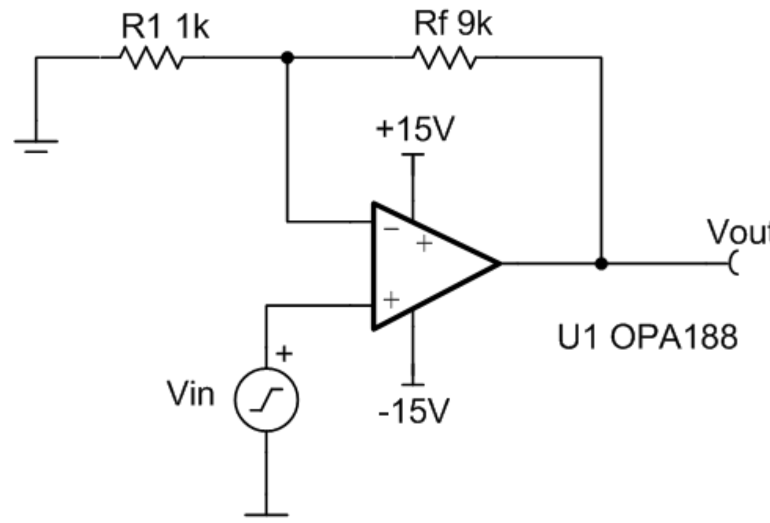


Figure 8. OPEN-LOOP GAIN AND PHASE vs FREQUENCY



3. Simulate the circuit below to determine the bandwidth. Check simulation with hand calculations.

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Low-Voltage Operation, V_S = ±2 V to < ±4 V (V_S = +4 V to < +8 V)

At T_A = +25°C, R_L = 10 kΩ connected to V_S / 2[(1)], and V_{CM} = V_{OUT} = V_S / 2[(1)], unless otherwise noted.

PARAMETER		CONDITIONS	MIN	TYP	MAX	UNIT
FREQUENCY RESPONSE						
GBW	Gain-bandwidth product			2		MHz
SR	Slew rate	G = +1		0.8		V/μs
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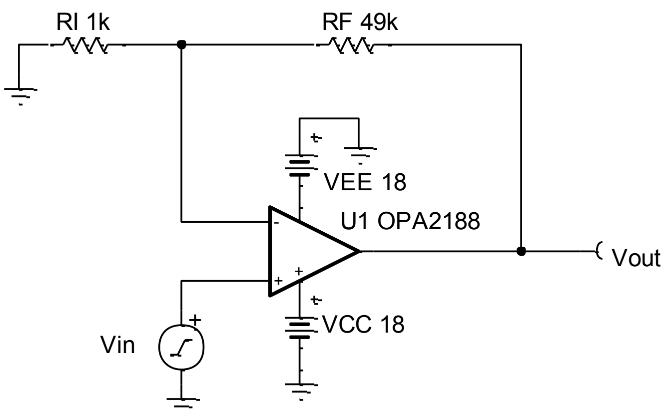
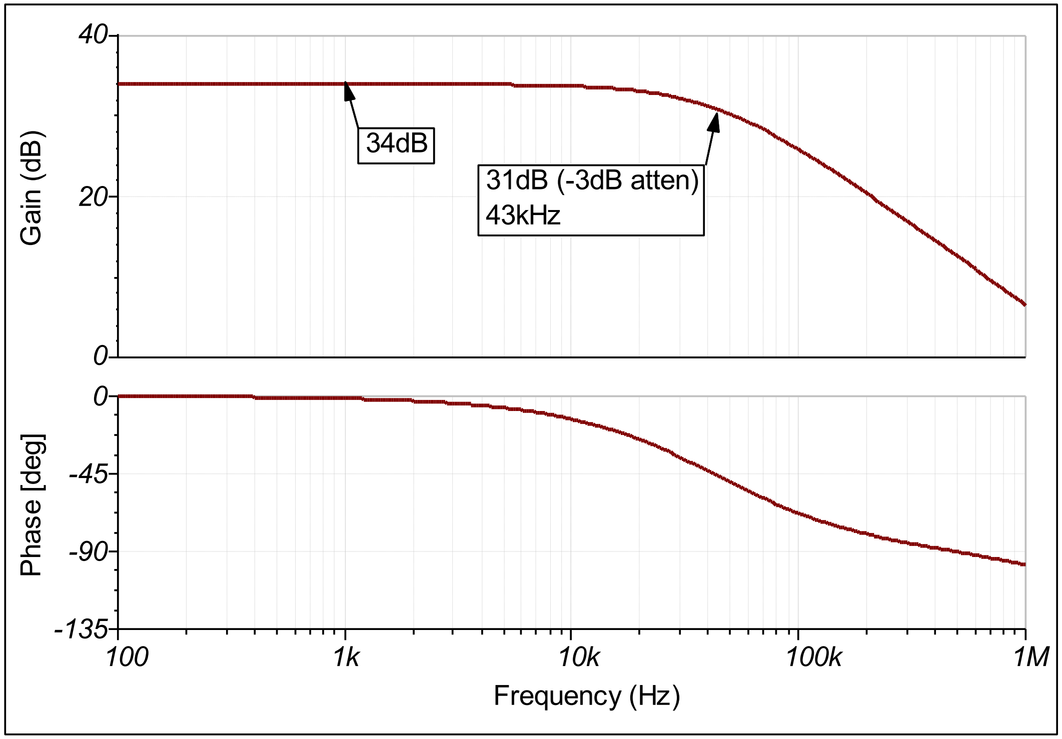


$$f_c = \frac{2MHz}{50} = 40kHz$$



1212 - Bandwidth 2 - problem3.TSC