Operational Amplifier Stability
Part 7 of 15: When Does R_O Become Z_O?
By Tim Green
Linear Applications Engineering Manager, Burr-Brown Products from Texas Instruments

A funny thing happened on the way to writing about "There must be six ways to leave your capacitive load stable". We chose a CMOS operational amplifier with a "rail-to-rail" output and measured the R_{OUT}, where there was no loop gain, at high frequency, to determine R_O. From this R_O measurement we predicted a second pole location in the amplifier's "modified Aol plot" due to a 1µF capacitive load. Much to our surprise our Tina SPICE simulation for this "modified Aol" plot was off by a factor of x5! This error was way outside of the acceptable bounds of any of our past first order analysis and thereby launched a detailed investigation of op amp output impedance.

Part 7 of this series will focus on op amp open loop output impedance, Z_O, for the two most common output topologies for small signal op amps. For traditional bipolar emitter-follower op amp output stages Z_O is well behaved and predominantly resistive (R_O) throughout the unity gain bandwidth of the op amp. However, for many CMOS rail-to-rail output op amps Z_O is both capacitive and resistive, within the unity gain bandwidth of the amplifier.

We will not, in this part, analyze the bipolar topology known as "all NPN output", which is most commonly used in Power Operational Amplifiers (op amps capable of operating in a linear region with high output currents from 50mA to greater than 10A).

Our expanded knowledge of output impedance will be critical to our correct prediction of "modified Aol plots" and an essential tool in our network synthesis techniques for stable op amp circuits.

Z_O for Bipolar Emitter-Follower Output Op Amps

A classical bipolar output stage of emitter-follower topology is shown in Fig. 7.1. With this type of output stage, R_O (small signal, open loop output resistance) is usually the dominant portion of Z_O (small signal, open loop output impedance). As well R_O is usually constant for a given DC current load. We will examine some rules-of-thumb for emitter-follower R_O and then use these rules of thumb to predict R_O for various values of DC output current. We will then check our predictions using Tina SPICE simulations.

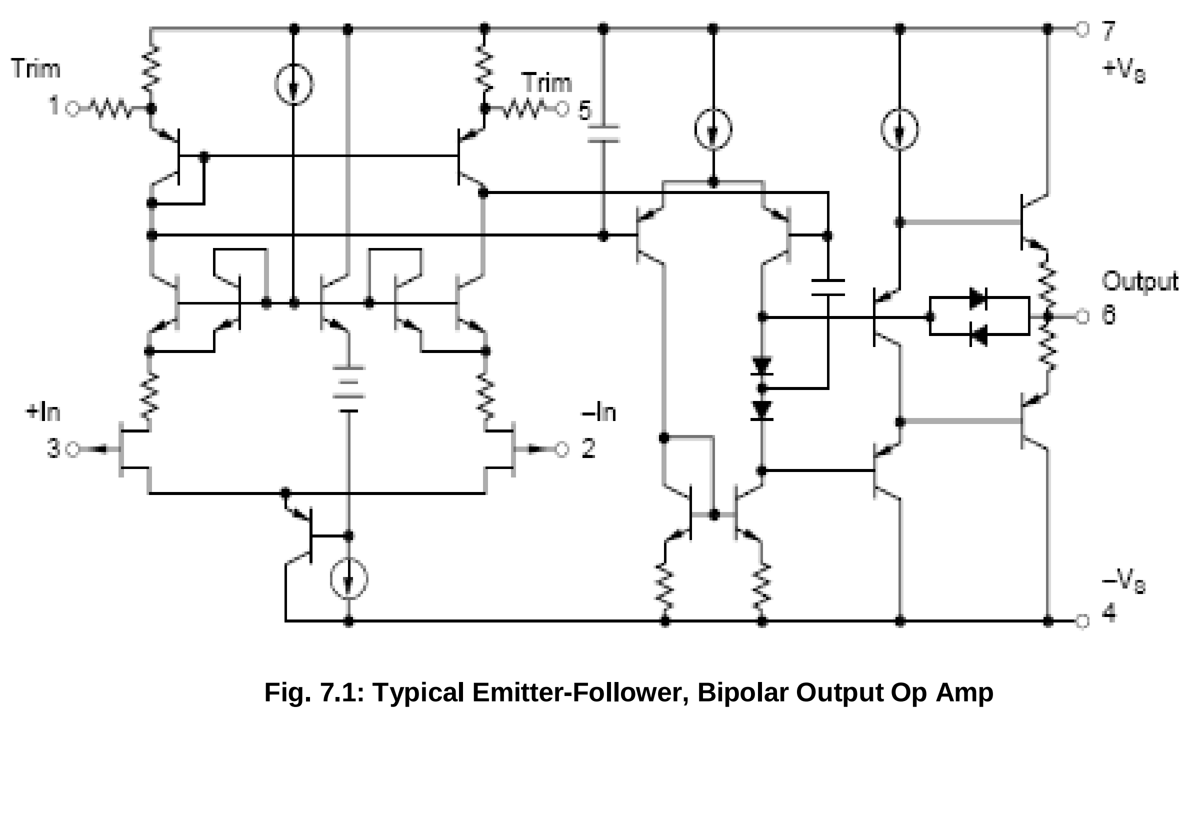


Fig. 7.1: Typical Emitter-Follower, Bipolar Output Op Amp

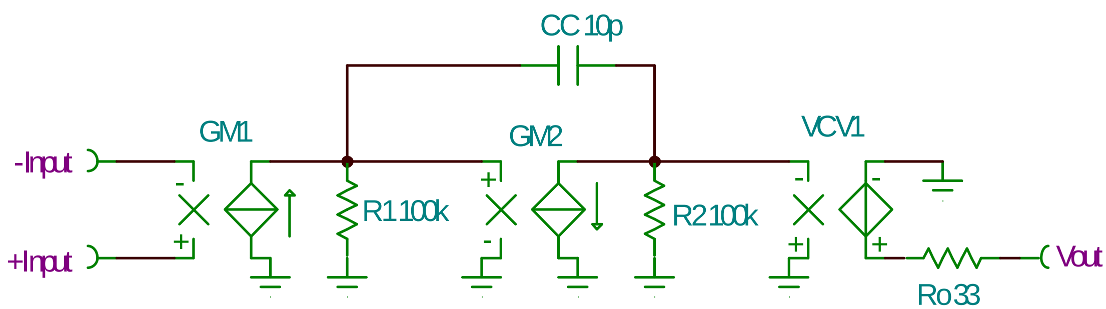
A typical emitter–follower, bipolar output op amp's specifications are shown in Fig. 7.2. This topology often yields low noise, low drift input specifications with the input bias currents in the nA region (i.e. 10nA). Some bipolar op amps use JFETs in the input stages to reduce input bias currents down to the low pA range. The common mode input range will usually be about 2V from either supply. The output voltage swing is typically restricted to within 2V or more of either supply rail and these op amps commonly get the best performance from using dual supplies (i.e. +/-5V to +/-15V).

OPA227
High Precision, Low Noise Bipolar Operational Amplifier

Input Specs		**AC Specs**	
Offset Voltage	75uV max	Open Loop Gain, RL = 10k	160dB typ
Offset Drift	0.6uV/C	Open Loop Gain, RL = 600	160dB typ
Input Voltage Range	(V-)+2V to (V+)-2V	Gain Bandwidth Product	8 MHz
Common-Mode Rejection Ratio	138dB typ	Slew Rate	2.3V/us
Input Bias Current	10nA max	Overload Recovery Time	1.3us
		Total Harmonic Distortion + Noise	0.00005%, f=1kHz
		Setling Time, 0.01%	
Noise		**Supply Specs**	
Input Voltage Noise	90nVpp, f=0.1Hz to 10Hz	Specified Voltage Range	+/-5V to +/-15V
Input Voltage Noise Density	3nV/rt-Hz @1kHz	Quiescent Current	+/-3.8A max
Input Current Noise Density	0.4pA/rt-Hz	Over Temperature	+/-4.2A max
Output Specs		**Temperature & Package**	
Vsat @ Iout = 1.2mA	2V max	Operating Range	-40C to +85C
Vsat @ Iout = 19mA	3.5V max	Package options	SO-8, DIP-8, DIP-14, SO-14
Iout Short Circuit	+/-45mA		

Fig. 7.2: Example Specifications: Emitter-Follower, Bipolar Output Op Amp

A simplified model for the classic emitter-follower, bipolar op amp uses two GM (current gain) stages followed by a transistor voltage follower output stage as shown in Fig. 7.3. Z_O, the open loop output impedance is dominated by R_O, open loop output resistance, and is constant over the unity gain bandwidth of the op amp.



Two GM (current gain) Stages
Output is *Voltage Output* Follower

Open Loop Output Impedance (Z_O) is dominated by R_O
Constant R_O over Op Amp Unity Gain Bandwidth

Fig. 7.3: Two-Stage Simplified Model: Emitter-Follower, Bipolar Output Op Amp

For most amplifiers the Class AB bias current in the output stage (with no load on the amplifier output) is about ½ of the quiescent current for the entire amplifier. For bipolar transistors R_O is proportional to 1/gm, where gm is the current transfer ratio or current gain of the transistor. Since gm is proportional to collector current I_C then we see that R_O is inversely proportional to I_C. As I_C increases from no load output current to full load output current R_O will decrease. This might imply that if we pull extremely high currents that R_O will go to zero. However, due to the physics of the transistor and the internal drive and bias arrangement this is not the case. We will measure R_O at the highest useable load current and define it as R_X. We will then measure R_O at no load current and derive a constant, K_Z for the given op amp circuitry that will enable us to predict what R_O does with any load current. From Fig. 7.4 we clearly see how the term emitter-follower output describes the path to the output pin of the op amp from the front end gm stages.

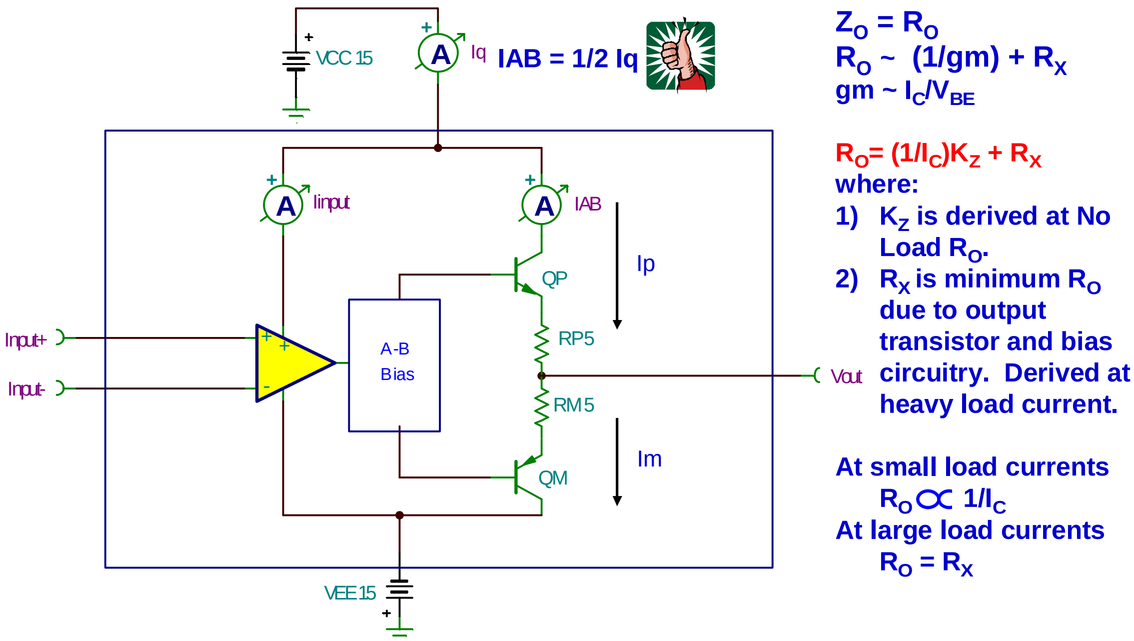


Fig. 7.4: Z_O Definition: Emitter-Follower, Bipolar Output Op Amp

Fig. 7.5 details our Emitter-Follower Z_O model with a constant value R_X, measured at full load current, and a series current-dependent resistor, with the transfer function of K_Z / I_C. Since we have a push (PNP Transistor) output stage and a pull (NPN transistor) output stage our Z_O model includes equivalent R_O models for each stage. The effective small signal ac output impedance looking back into the output pin will be the parallel combination of the push and pull output stages. Remember that for our small signal AC model of Z_O both power supplies, VCC and VEE, will appear as an AC short.

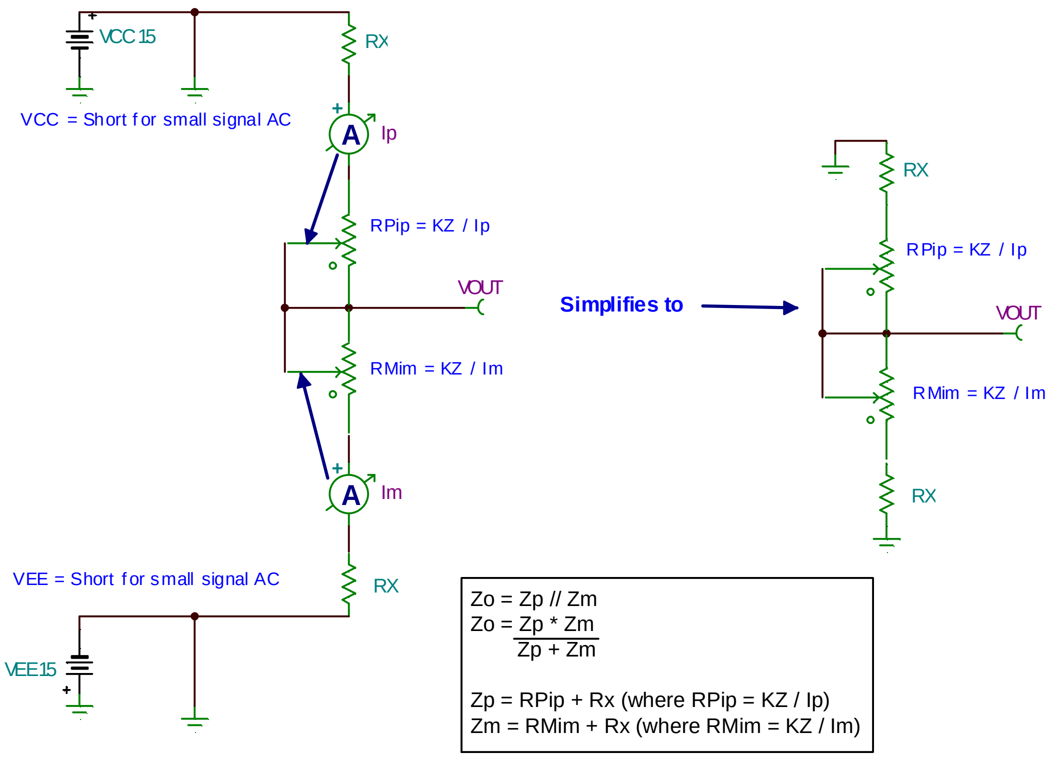


Fig. 7.5: Z_O Model: Emitter-Follower, Bipolar Output Op Amp

Not all SPICE macro-models for op amps are equal. As such any simulations we do to investigate output impedance, Z_O, must be done on macro-models which correctly model the output with real devices and proper class A-B bias circuitry which accurately models the actual device. It is not often clear from a given manufacturer's model if this is adequately modeled. Most SPICE models for precision op amps developed by the Burr-Brown division of Texas Instruments, over the last 4 years, are built by W. K. Sands of Analog & RF Models (http://www.home.earthlink.net/%7Ewksands/). These SPICE models of the op amp are extremely good representations of the actual silicon op amp and as shown above will include a detailed list of features including proper modeling of the output stage as well as the class AB bias circuitry. Refer to Fig. 7.6.

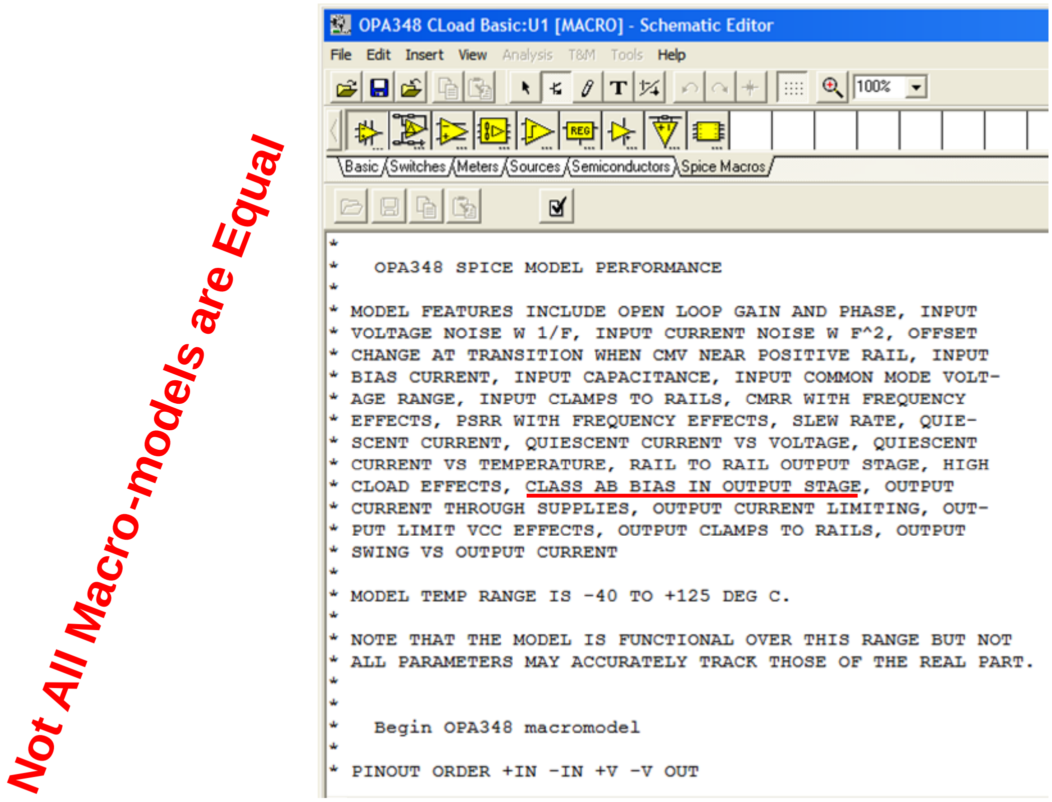


Fig. 7.6: Not All SPICE Op Amp Models Are Equal!

Since we were not able to find a bipolar emitter-follower op amp macro-model with accurate class A-B biasing and real transistor outputs for an accurate analysis of real world behavior we built our own for evaluation purposes. In this slide we see an ideal front end implemented with a voltage-controlled-voltage source with open loop gain of 160dB (x100E6). The output transistors, QP and QM, are biased on with a simplified class A-B bias circuit. For our op amp we set the maximum output current at 27mA and therefore to find our R_O parameter R_X we will test with a load current of +27mA. A simple Z_O test circuit in Tina SPICE is easy to build through the use of an “input resistor” RL and a “feedback” inductor LF. See Fig. 7.7. At DC the inductor is a short and RL, combined with the applied voltage, Vdc, sets the DC load current as shown. With our ideal 1T-Henry (1E12 Henry) inductor we have a DC closed loop path so SPICE can find an operating point, but for any AC frequency of interest we have an open. Now if we excite our circuit with a 1A, AC source, Itest, then V_{OUT} becomes Z_O after a math conversion from dB. Notice for this heavy load, I_{OUT} =+27mA, that QM is essentially off and QP is on and dominates the output impedance.

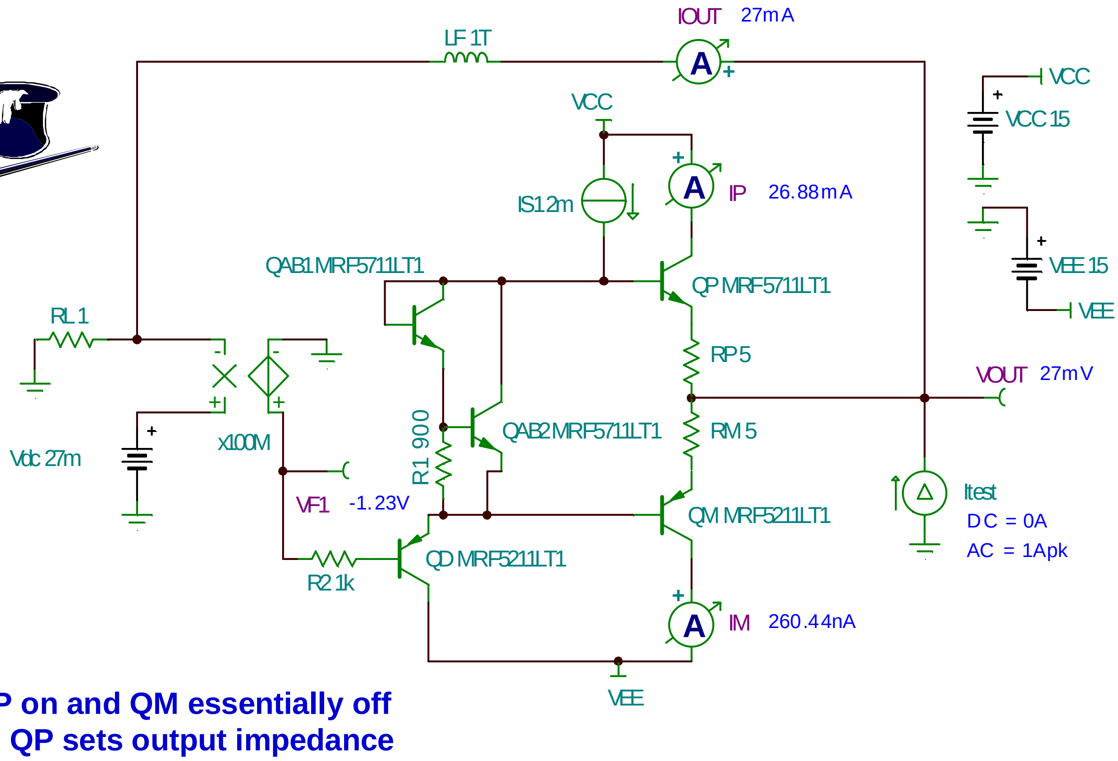


Fig. 7.7: Z_O, Heavy Load I_{OUT} = +27mA

We see in Fig. 7.7 our measured results for Z_O with I_{OUT} = +27mA out of our bipolar emitter-follower output op amp. The initial SPICE results will be plotted in "linear-dB". If we choose "logarithmic" on the y-axis this will result directly in ohms for Z_O. The logarithmic scale on the y axis will become handy when we look at other Z_O plots that are not constant over the frequency bandwidth (i.e. CMOS RRO).

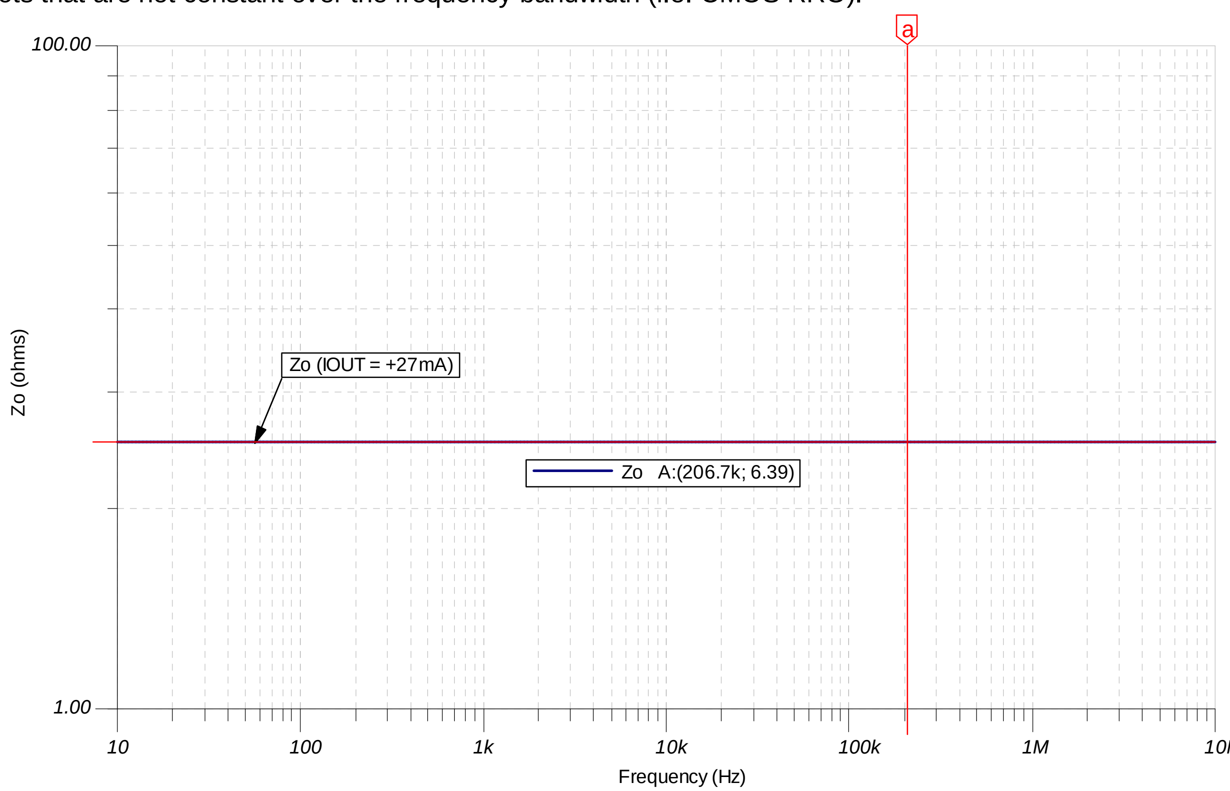


Fig. 7.8: Z_O AC Plot, Heavy Load, I_{OUT} = +27mA

Fig. 7.9 shows our equivalent Heavy Load Z_O model for I_{OUT} = +27mA. R_X was measured to be 6.39Ω. We will assume that the output transistors (QP and QM) used are close in characteristics and therefore assign R_X the same value for each. If we wanted we could re-run our analysis and measure R_X for I_{OUT} = -27mA. The results would be close enough for us to ignore the difference. From this model we assume RMim will be high impedance and therefore have no measurable effect on R_O. Also we assume RPip will be much smaller than R_X.

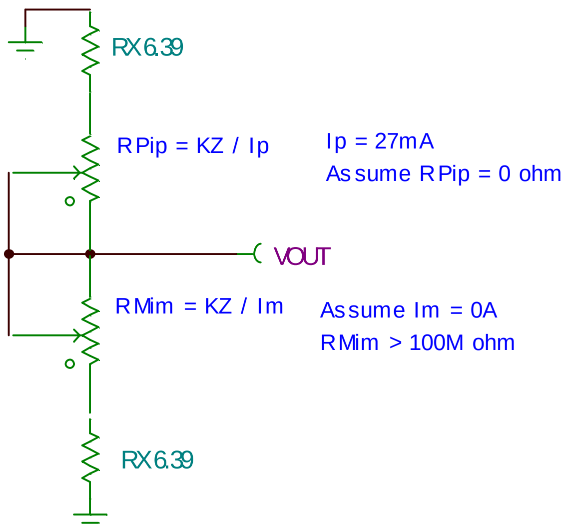
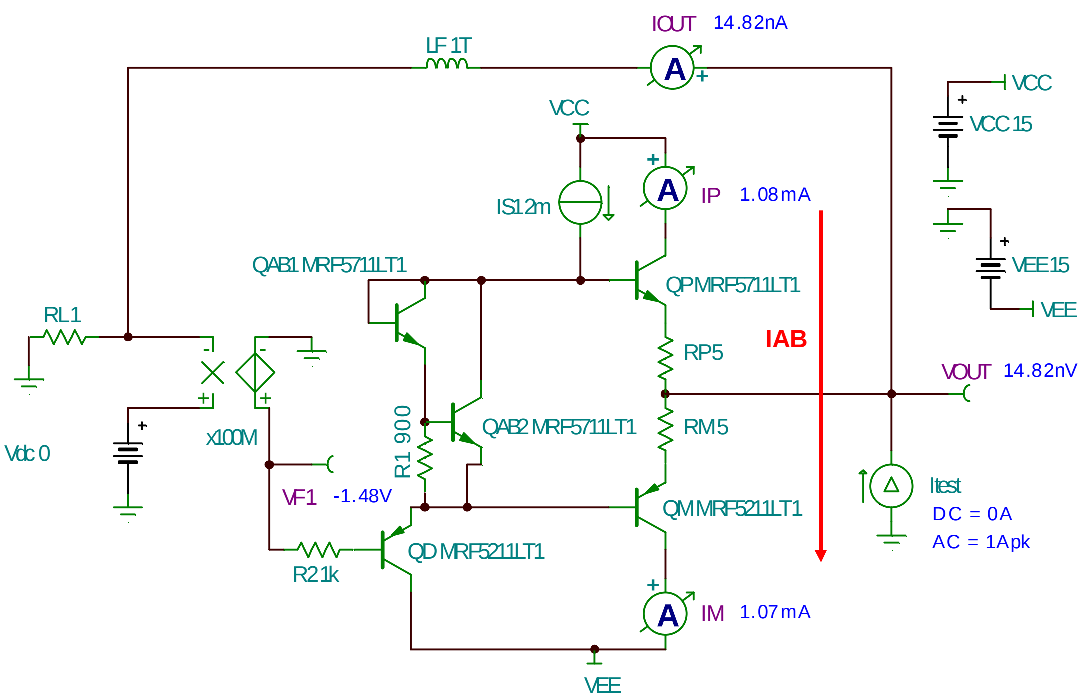


Fig. 7.9: Heavy Load Z_O Model

The No Load condition for our class A-B bias emitter-follower output is detailed in Fig. 7.10. The class A-B bias current, I_{AB}, is set to 1.08mA. For no load at the output we see that both output transistors, QP and QM, are on and each will contribute equally to Z_O.



QP and QM are equally biased on and contribute equally to Z_O

Fig. 7.10: Z_O, No Load, I_{OUT} = 0mA

As shown in Fig. 7.11 the No Load Z_O is measured to be 14.8Ω. This information, along with the Heavy Load value for Z_O (which resulted in a value for R_X) will allow us to complete our small signal Z_O model by computing the constant K_Z.

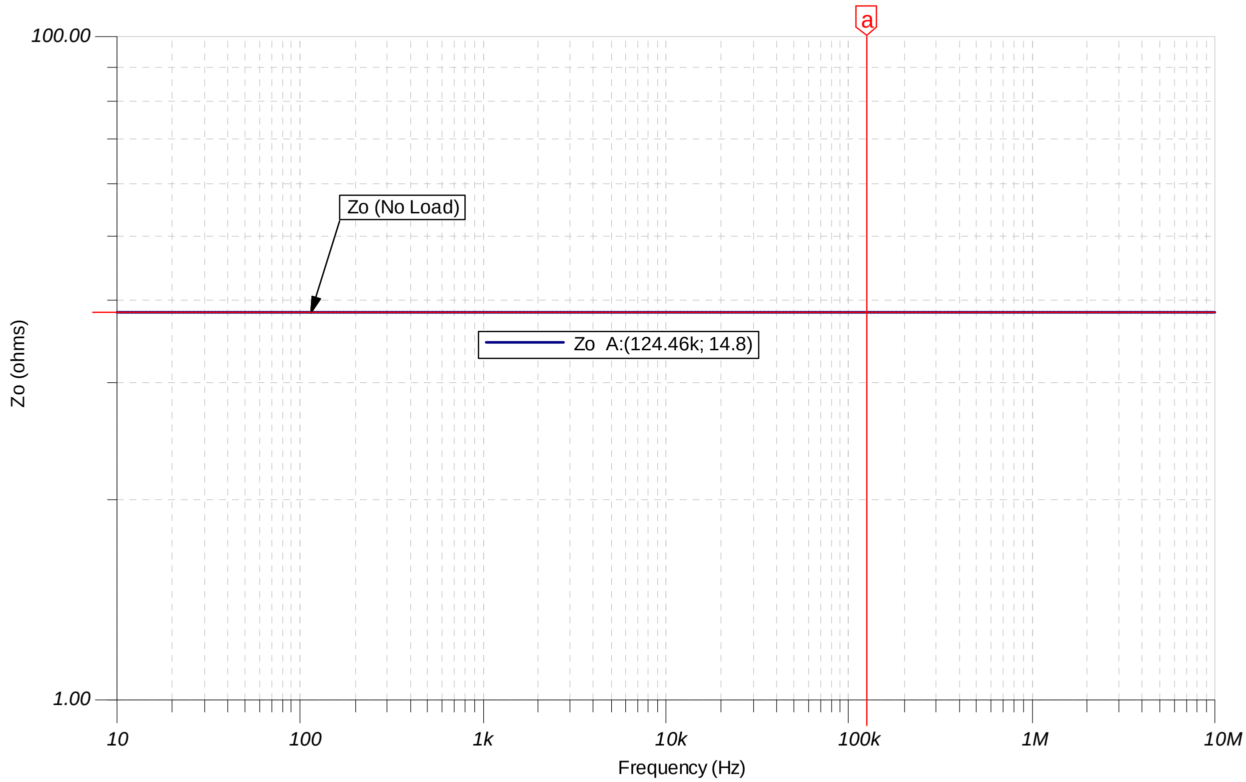


Fig. 7.11: Z_O AC Plot, No Load, I_{OUT} = 0mA

In Fig. 7.12 we use our Emitter-Follower Z_O Model for the No Load condition. We use our results from the Heavy Load condition and fill in values for R_X. Now we need to derive K_Z based on Z_O at no load and the assumption that the characteristics of both output transistors, QP and QM are similar. This derivation is detailed above and we see K_Z is found to be 0.0250668.

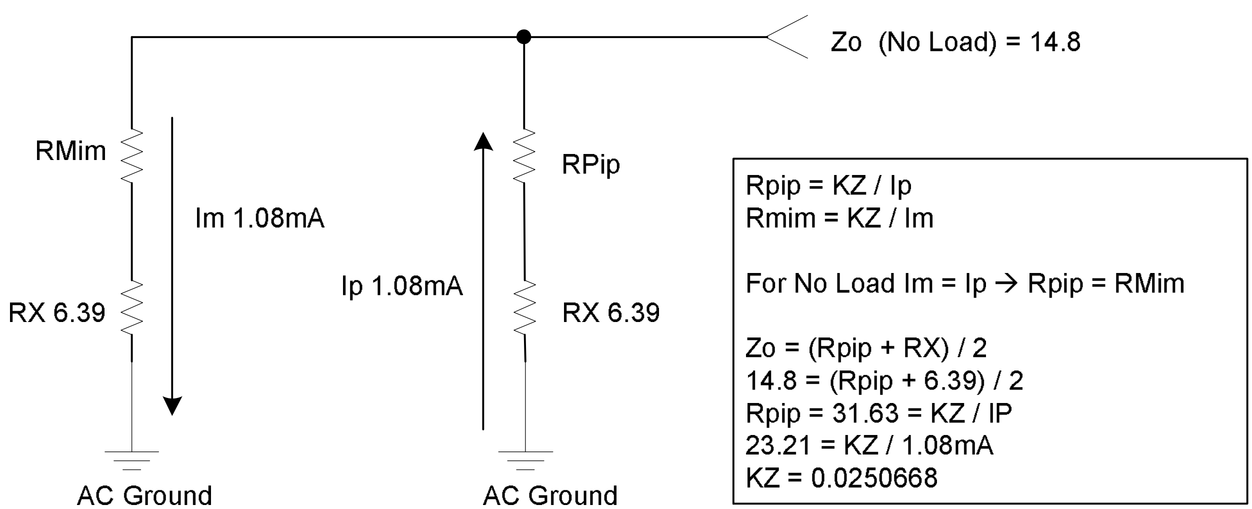
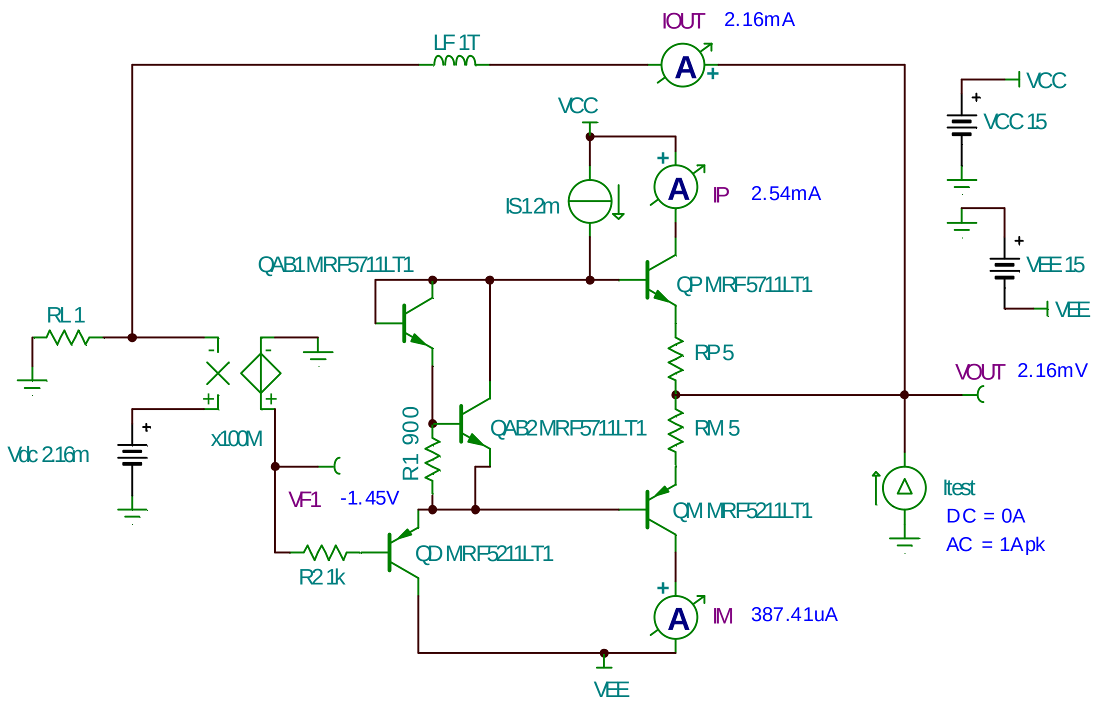


Fig. 7.12: No Load Z_O Model

So now let's test our Emitter-Follower Z_O model. We will use a DC current out of QP which is about 2 x I_{AB}, that is twice the class A-B bias current. This should about turn off QM and force Z_O to be dominated by the R_O due to QP. From Fig. 7.13 we see this is approximately true. This is a good illustration as to how real world class A-B bias schemes work. We see that as load current increases positive the entire class A-B bias current begins to shift into the positive output transistor, QP. As the load current becomes negative QM begins to receive the entire class A-B bias current until QP is completely turned off at heavy negative load currents.



Both QP and QM on and contribute to Z_O but QP dominates due to lowest impedance

Fig. 7.13: Z_O, Light Load, I_{OUT} = +2xI_{AB} (2.16mA)

Our Emitter-Follower Light Load Z_O Model is illustrated in Fig. 7.14. Using our known values of R_X and K_Z we compute the equivalent Z_O we expect and then run our Tina SPICE simulation as with results shown in the next slide. We calculated Z_O at light load to be 13.2326Ω with the Tina SPICE measured at 12.85Ω. This is close enough to use for any analysis we are interested in. If we took the time to investigate we would find that QP and QM do not have exactly the same characteristics.

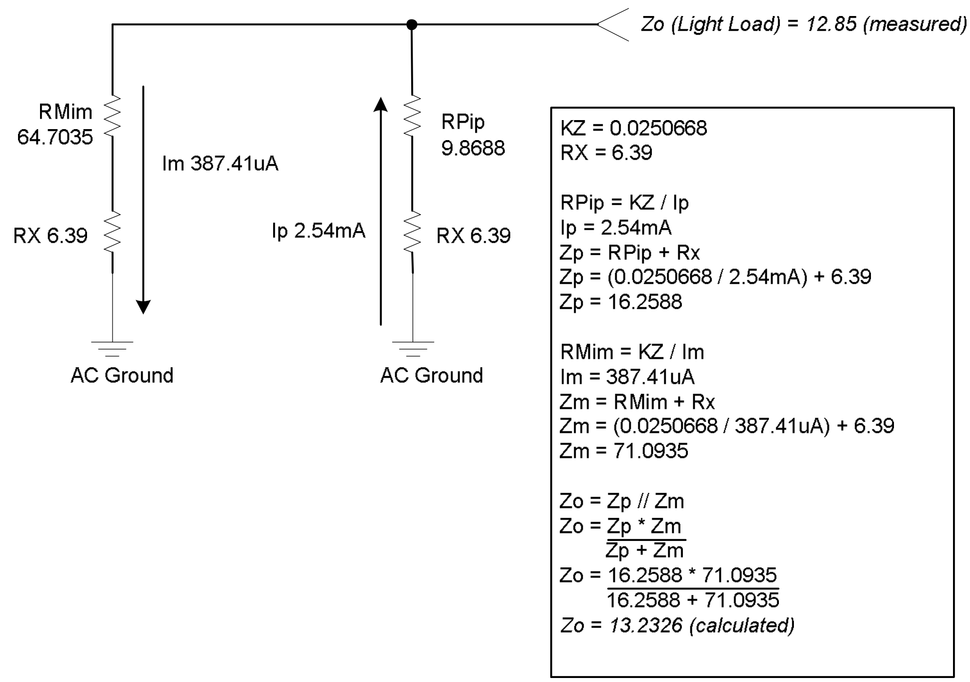


Fig. 7.14: Light Load Z_O Model

Tina SPICE results in Fig. 7.15 are for Z_O at light load.

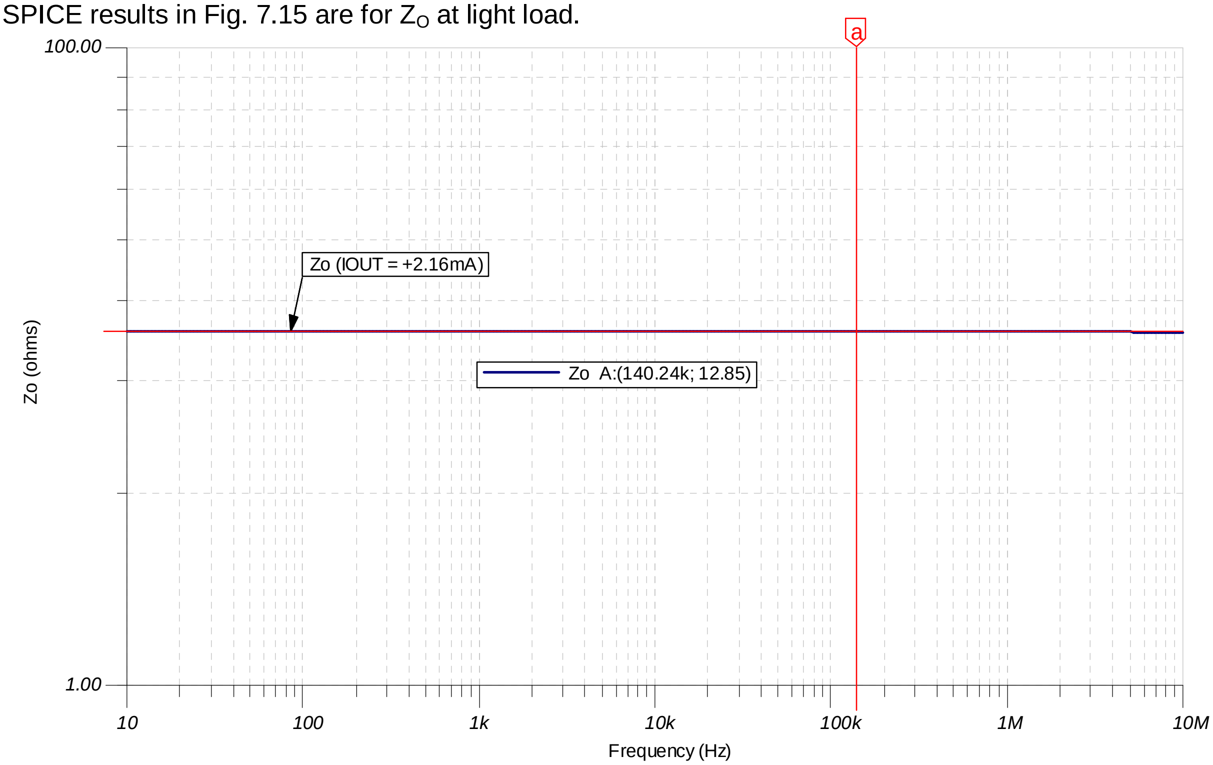


Fig. 7.15: Z_O AC Plot, Light Load, I_{OUT} = +2.16mA

Now our complete set of curves for Emitter-Follower Z_O can be constructed in Fig. 7.16. As can be seen in Fig. 7.16, Z_O is dominated by R_O, constant over the unity gain bandwidth of the op amp, and R_O goes down with increasing load currents. Notice that Z_O was plotted for both Source and Sink currents at a Light Load and Heavy load with no significant difference in source or sink Z_O. These key curves for Z_O should be included in every bipolar emitter follower op amp data sheet.

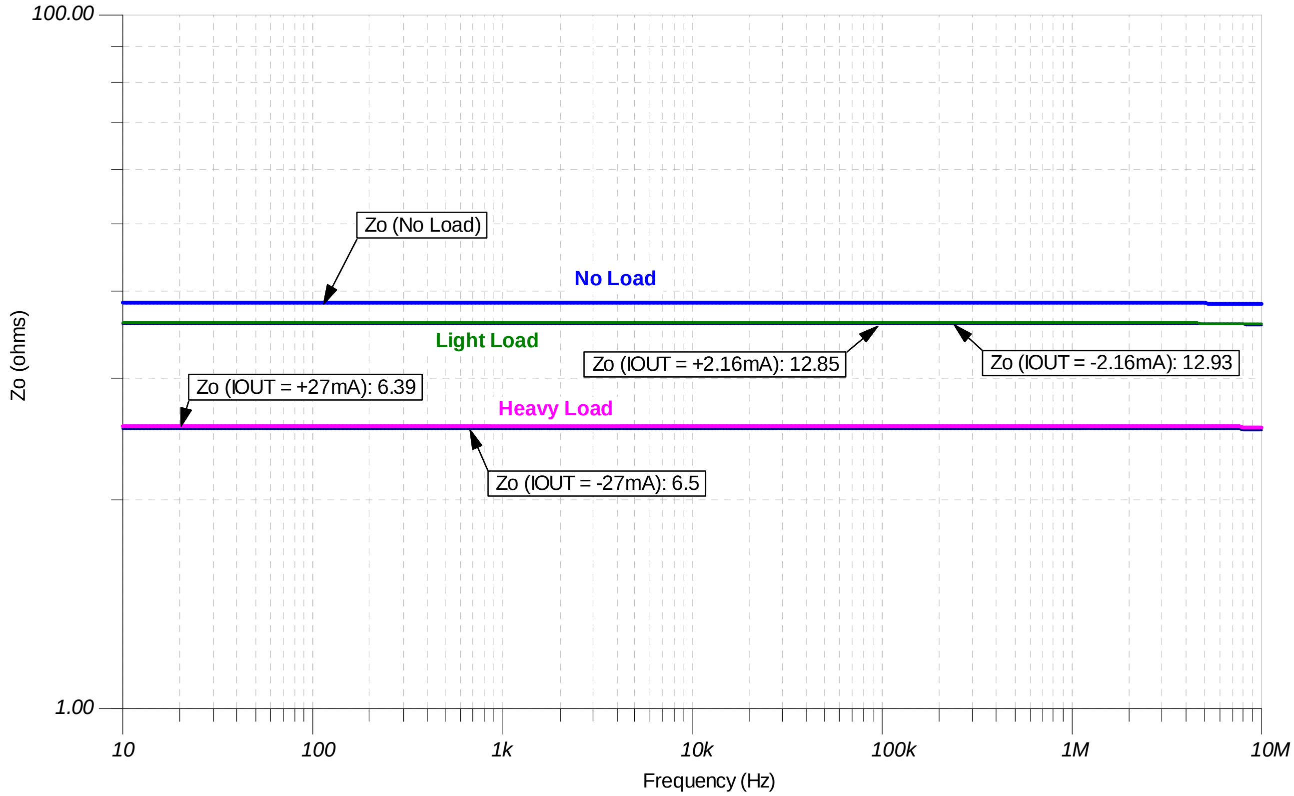
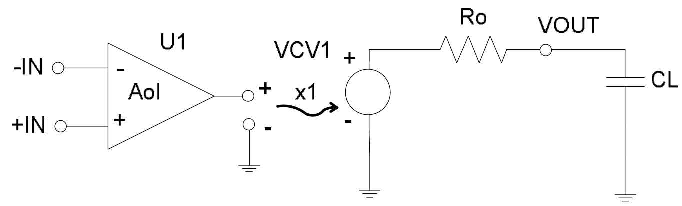
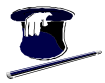


Fig. 7.16: Complete Z_O Curves: Bipolar Emitter-Follower

Z_O and Capacitive Loads for Bipolar, Emitter-Follower Output Op Amps

For capacitance loads on the output of Emitter-Follower stages we will use the model in Fig. 7.17. We are either given in a data sheet or can measure the op amp's Aol curve with no capacitive load. R_O will react with CL and form a second pole, fp2, in the op amp's unloaded Aol curve.





$$fp2 = \frac{1}{2*\pi*CL*RO}$$

U1: Op Amp DC and AC Aol Function
VCV1: x1 Voltage-Controlled-Voltage-Source
Ro: Open Loop AC Small Signal Output Resistance
CL modifies Aol Curve.

Fig. 7.17: Bipolar Emitter-Follower Z_O and Capacitive Loads

We will load our Emitter-Follower Bipolar op amp with many different capacitive loads and test it for the location of the additional pole, fp2, due to R_O and CL. The circuit in Fig. 7.18 uses LT to establish a DC operating point as a short at DC. At any AC frequency of interest LT is an open so we can look at a modified Aol curve. CT is open for DC and a short for any AC frequency of interest and connects the AC test source VG1 into the circuit. By inspection we see that Aol = VOA / VM.

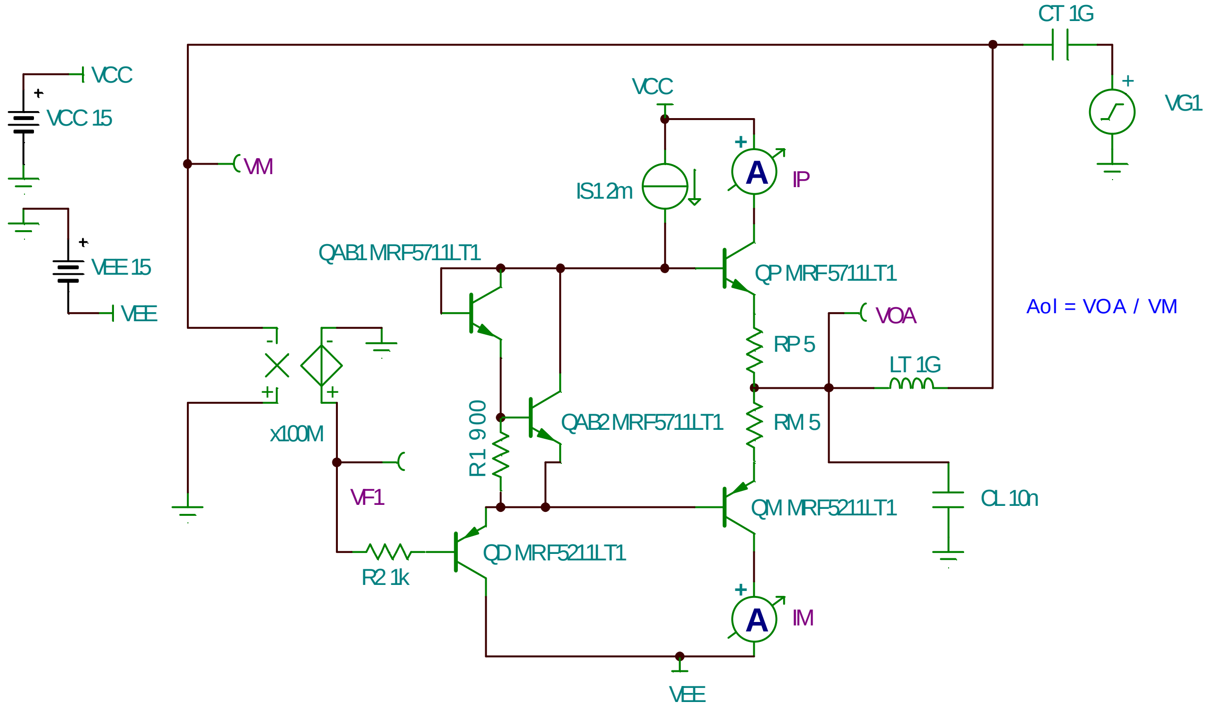


Fig. 7.18: Tina SPICE Circuit for Modified Aol Measurement

The resultant modified Aol curves due to several different capacitive loads are shown in Fig. 7.19.

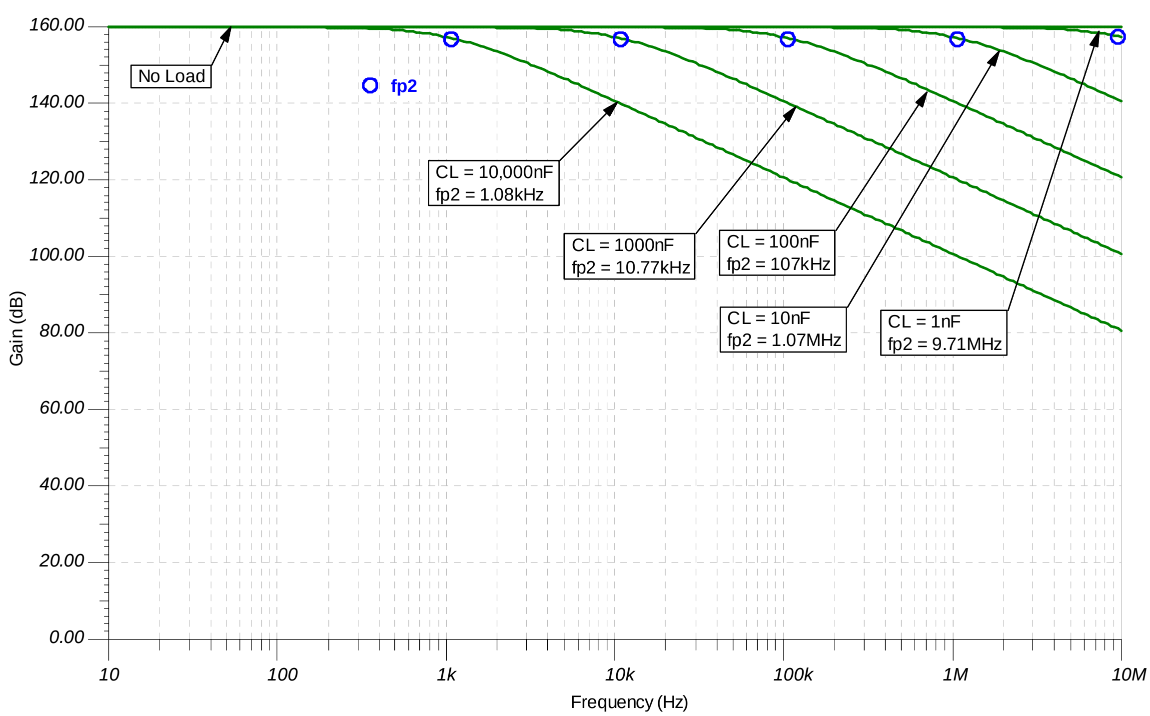


Fig. 7.19: Modified Aol Curves for Different Values of CL

Our predicted locations of the pole, fp2, due to R_O and CL, in the modified Aol curve are detailed in Fig. 7.20. Also shown are the actual Tina SPICE measured locations for each respective fp2. For use in stability synthesis techniques there is no significant error between the Tina SPICE actual values for fp2 and our predicted values.

RL	No Load		
Ro	14.8		
		Predicted	**Actual**
CL	**CL**	**fp2**	**fp2**
	(farads)	(Hz)	(Hz)
1nF	1.00E-09	10753712	9710000
10nF	1.00E-08	1075371	1070000
100nF	1.00E-07	107537	107000
1000nF	1.00E-06	10754	10770
10,000nF	1.00E-05	1075	1080

Fig. 7.20: fp2 Locations for Different CL: Predicted and Actual

Z_O Summary for Bipolar Emitter-Follower Output Op Amps

Fig. 7.21 summarizes the key characteristics of Z_O for a bipolar emitter-follower op amp. Within the unity gain bandwidth of the op amp Z_O is dominated by R_O and is constant with frequency. As DC output load current increases R_O decreases making R_O inversely proportional to I_{OUT}. Capacitive loads, CL, interact with R_O to form a second pole in the original op amp Aol curve. We can use this modified Aol curve to help synthesize the proper closed loop compensation for good stability. R_O does change with process and temperature. A good rule-of-thumb for this change which includes process and temperature changes is 0.65* $R_O$typ at -55C to 1.5* $R_O$typ at 125C, where $R_O$typ is the 25C typical value for R_O. There are always exceptions to the rules-of-thumb we have developed for open loop output impedance of bipolar emitter-follower op amps. The most complete and accurate data for Z_O should be obtained from the op amp manufacturer or measured.

ØZ_O is Dominated by R_O

ØZ_O is Constant over Op Amp Unity Gain Bandwidth

ØZ_O is Inversely Proportional to I_{OUT}

ØR_O and CL form a Second Pole to create a Modified Aol

ØR_O Change with Process and Temperature:
- **ü R_O @ -55C = 0.65 * $R_O$typ (i.e. 65 ohms)**
- **ü R_O @ 25C = $R_O$typ (i.e. 100 ohms)**
- **ü R_O @ +125C = 1.5 * $R_O$typ (i.e. 150 ohms)**

ØUse $R_O$typ for Stability Synthesis
- **ü Decade Rules-of-Thumb will provide Design Margin**

Fig. 7.21: Z_O Summary for Bipolar Emitter-Follower

Z_O for CMOS RRO (Rail-to-Rail Output) Op Amps

A typical CMOS RRO op amp topology is shown in Fig. 7.22. With this type of output stage R_O (small signal, open loop output resistance) is usually the dominant portion of Z_O (small signal, open loop output impedance) at high frequencies. R_O is inversely proportional to DC load current at most currents. However, at light load currents R_O is proportional to DC load currents. At mid and low frequencies Z_O is usually capacitive. The op amps Aol curve will be affected at low frequencies due to RL (resistive load on output) interacting with the capacitive portion of Z_O.

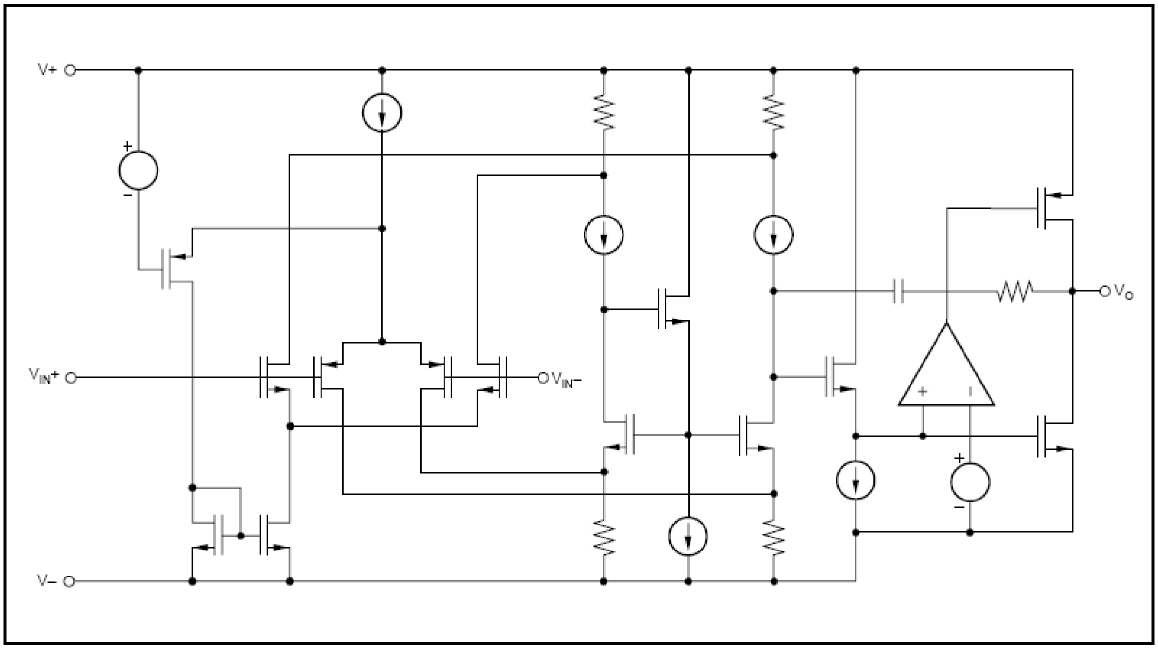


Fig. 7.22: Typical CMOS RRO Op Amp

An example CMOS RRO op amp's specifications are listed in Fig. 7.23. The OPA348 is also a RRI (Rail-to-Rail input) op amp. The CMOS RRIO (Rail-to-Rail Input/Output) topology is ideal for single supply applications with close swing to the rail on both the input and output, low quiescent current, and low input bias currents. Noise will usually be considerably higher than the bipolar emitter–follower op amp.

OPA348
1MHz, 45uA, CMOS, RRIO Operational Amplifier

Input Specs

Offset Voltage	5mV max
Offset Drift	4uV/C
Input Voltage Range	(V-)-0.2V to (V+)+0.2V
Common-Mode Rejection Ratio	82dB typ
Input Bias Current	10pA max

Noise

Input Voltage Noise	10uVpp, f=0.1Hz to 10Hz
Input Voltage Noise Density	35nV/rt-Hz @1kHz
Input Current Noise Density	4fA/rt-Hz

Output Specs

Vsat @ Iout = 27uA	25mV max
Vsat @ Iout = 540uA	125mV max
Vsat @ Iout = 5mA	1V max
Iout Short Circuit	10mA

AC Specs

Open Loop Gain, RL = 100k	108dB typ
Open Loop Gain, RL = 5k	98dB typ
Gain Bandwidth Product	1 MHz
Slew Rate	0.5V/us
Overload Recovery Time	1.6us
Total Harmonic Distortion + Noise	0.0023%, f=1kHz
Setling Time, 0.01%	

Supply Specs

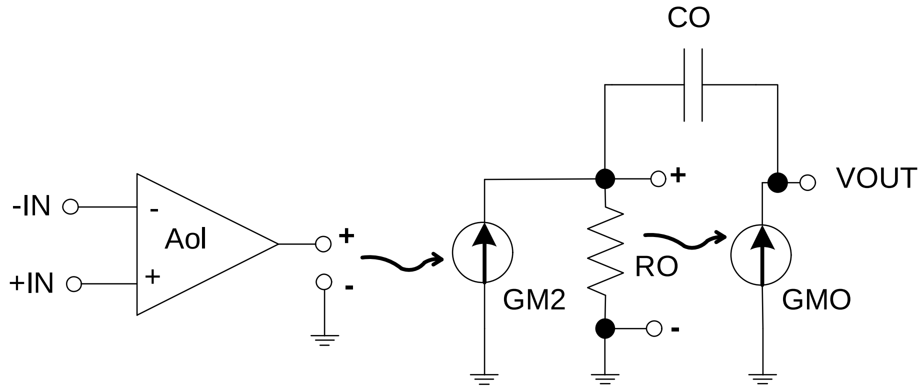
Specified Voltage Range	2.5V to 5.5V
Quiescent Current	65uA max
Over Temperature	75uA max

Temperature & Package

Operating Range	-40C to +125C
Package options	SOT23-5, SO-8, SC70-5

Fig. 7.23: Example Specifications: CMOS RRIO Op Amp

Fig. 7.24 is our simplified model for a typical CMOS RRO op amp uses a voltage output differential front end which controls a current source, GM2. GM2 drives RO, developing a voltage which controls GMO, the output current source. Capacitor CO feeds back into the RO, GM2 node. From this simplified model we observe that at high frequencies $Z_O = R_O$. As we go from high frequency towards medium and low frequencies we expect to see the effects of CO and will therefore look for Z_O to be capacitive.

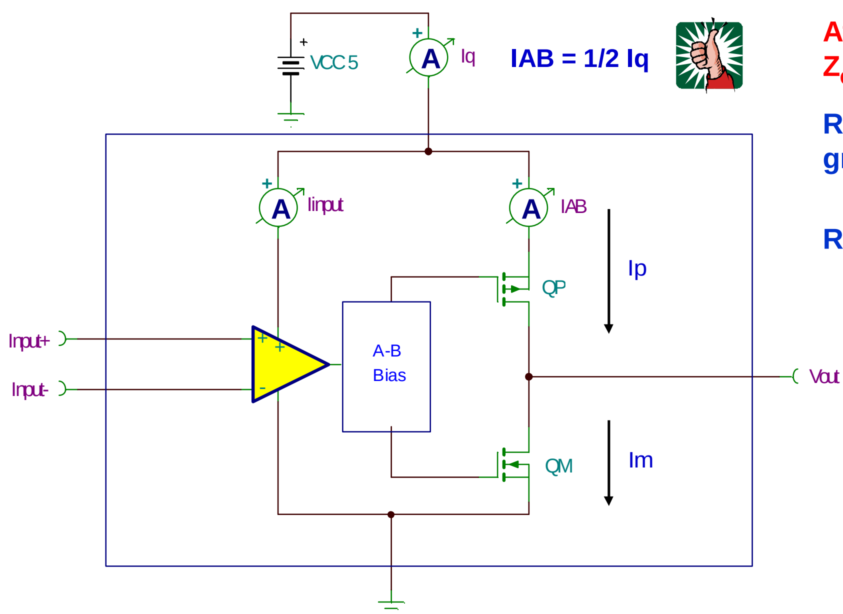


Output is two GM (current gain) Stages
Output is *Current Source* GMO (ideal current source has infinite impedance)

Output Impedance (Z_O) is dominated by R_O at High Frequencies
Z_O will look capacitive at Low and Medium Frequencies

Fig. 7.24: Simplified Model: CMOS RRO Op Amp

As shown in Fig. 7.25 most CMOS RRO amplifiers the class AB bias current in the output stage (with no load on the amplifier output) is about ½ of the quiescent current for the entire amplifier. At high frequencies $Z_O = R_O$. R_O is proportional to gm (current transfer ration for MOSFET). But for MOSFETs gm is inversely proportional to the square-root of I_D (drain current).



At High Frequencies:
$Z_O = R_O$

$R_O \sim (1/gm)$
$gm \sim 2\sqrt{(K*ID)}$

$R_O \propto \dfrac{1}{2\sqrt{(K*I_D)}}$

Fig. 7.25: Z_O Definition: CMOS RRO Op Amp

Fig. 7.26 details our CMOS RRO R_O model which consists of current controlled resistors for each half of the push (QP) and pull (QM) output MOSFETs. Each of these current controlled resistors, RPip and RMim, are proportional to the square root of the drain current flowing through each respective MOSFET. When looking back into the output terminal of the op amp these two current controlled resistors appear in parallel for a net value of R_O. The equation for the parallel combination of these resistances creates a mathematical equation which yields an unexpected transfer function. For small increases in I_{OUT}, R_O will increase until one of the output MOSFETS gets completely turned off and out of class A-B bias mode.

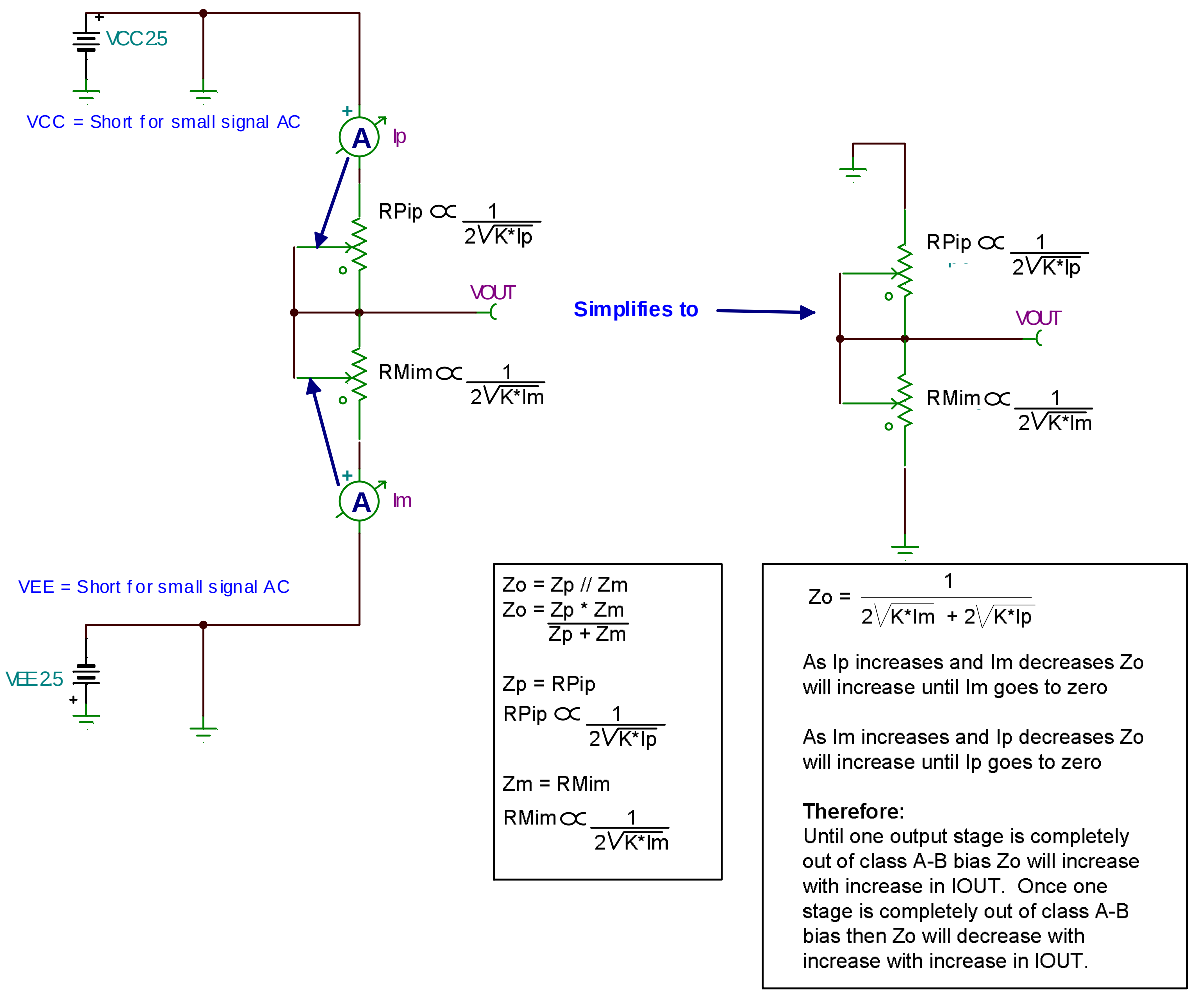


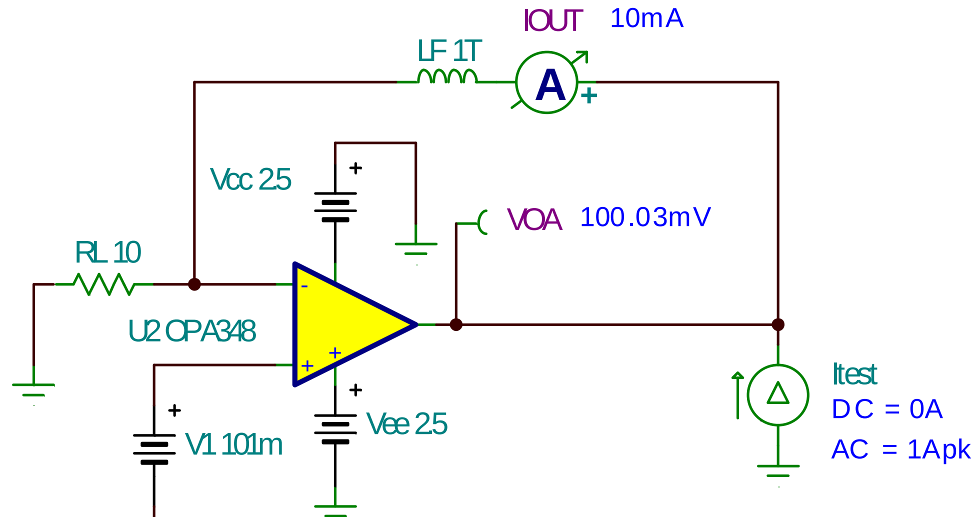
Fig. 7.26: R_O Model: CMOS RRO Op Amp

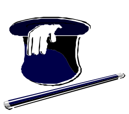
The example calculation in Fig. 7.27 shows the unique relationship of R_O for small changes in I_{OUT}. We see a 200Ω R_O when both devices have equal current flowing through QP and QM of 22uA in the class A-B bias mode. As Im increases, indicating I_{OUT} is increasing in current sunk into the op amp output, QP receives less and less current down through it until it is essentially turned off at Im = 44μA. It is at this point that we see R_O at a maximum (R_O Max = 282.25 ohms). Now for higher I_{OUT} currents R_O will decrease.

CMOS RRO Ro Calculator					
K=	0.071				
Ip	**Rp**	***Im***	**Rm**	**Ro**	
2.2000E-05	4.0006E+02	2.2000E-05	4.0006E+02	2.0003E+02	
1.1000E-05	5.6578E+02	3.3000E-05	3.2665E+02	2.0709E+02	
5.5000E-07	2.5302E+03	4.3450E-05	2.8467E+02	2.5588E+02	
5.5000E-08	8.0013E+03	4.3950E-05	2.8305E+02	2.7338E+02	
5.5000E-09	2.5302E+04	4.3990E-05	2.8292E+02	2.7979E+02	
1.0000E-12	***1.8765E+06***	***4.4000E-05***	***2.8289E+02***	***2.8285E+02***	***Ro Max***
1.0000E-12	1.8765E+06	8.8000E-05	2.0003E+02	2.0001E+02	
1.0000E-12	1.8765E+06	1.7600E-04	1.4144E+02	1.4143E+02	
1.0000E-12	1.8765E+06	3.5200E-04	1.0002E+02	1.0001E+02	

Fig. 7.27: Example of R_O Increasing/Decreasing Characteristic

We have chosen the OPA348, CMOS RRIO op amp, to investigate CMOS RRO Z_O. This device is known to have an extremely accurate SPICE macro-model and the Z_O characteristics were confirmed through lab bench testing. Tina SPICE will allow us a convenient way to look at the characteristics of Z_O. Our first Z_O measurement will be at the maximum load current of 10mA. Note in our test circuit of Fig. 7.28 the current meter IOUT in our test circuit to ensure that we could control exactly the DC value of I_{OUT} to be 10mA. Simply dividing V1 by RL does not exactly account for the input offset voltage characteristics of the op amp which may add an unacceptable error.





NOTE:
IOUT current meter provides accurate measure of IOUT
Ideally IOUT = V1 / RL but this does not account for input offset voltage!

Fig. 7.28: Z_O, Heavy Load, I_{OUT} = +10mA

The AC plot of Z_O for I_{OUT} of 10mA has a high frequency R_O component of 34.79Ω. Z_O is clearly capacitive for frequencies lower than about 10kHz. We expect at this output current for R_O to be the lowest we will see it since QM is entirely off and QP has all output stage current flowing through it.

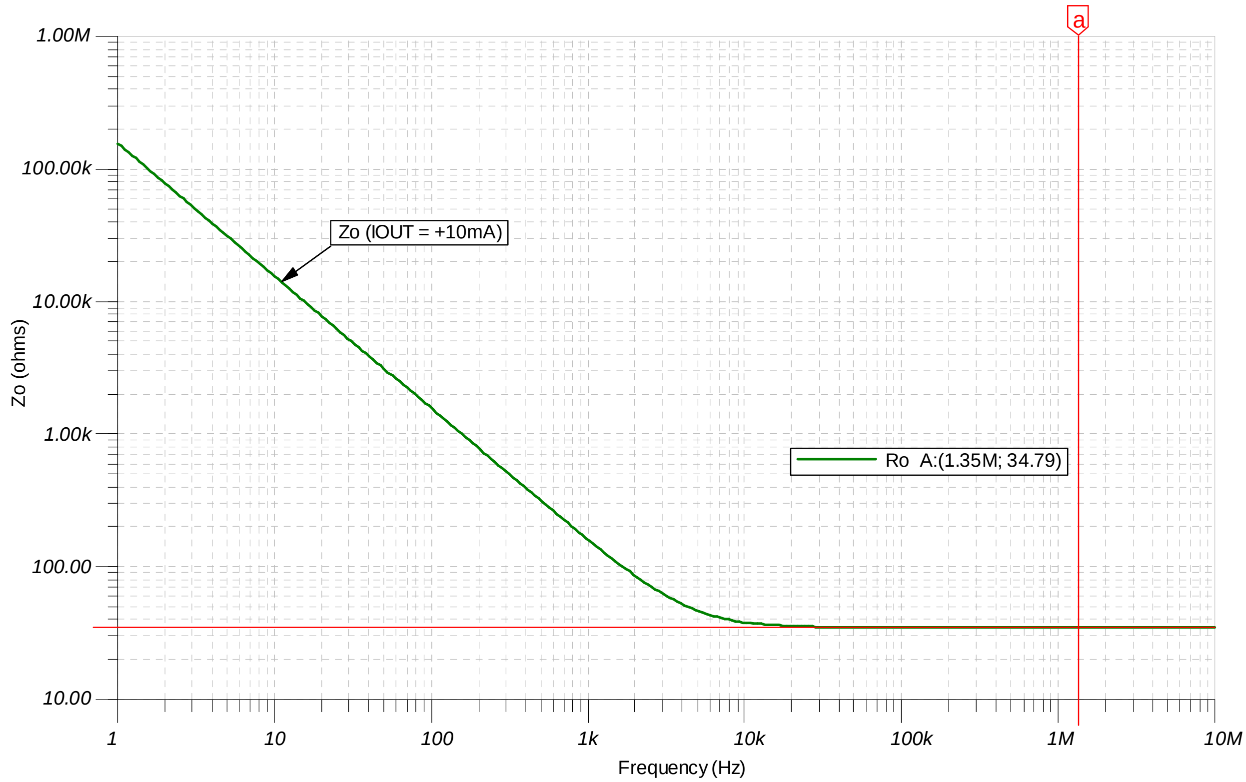
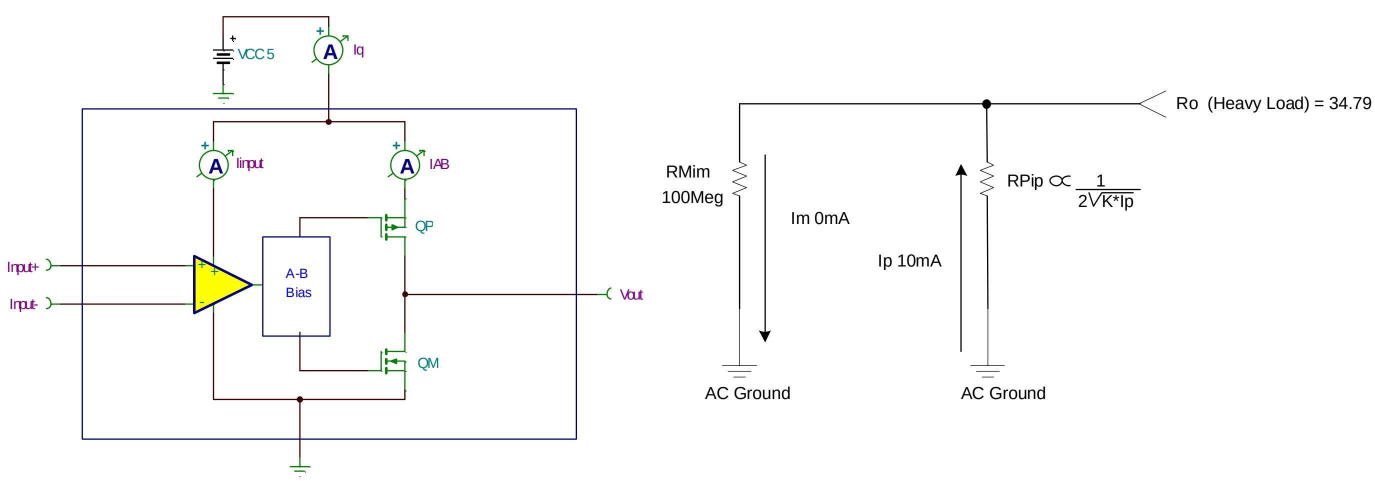


Fig. 7.29: Z_O AC Plot, Heavy Load, I_{OUT} = +10mA

Our Heavy Load R_O model in Fig. 7.30 confirms that, at this output current, R_O should be the lowest since QM is entirely off and QP has all output stage current flowing through it.



QP on and QM essentially off so QP sets output impedance

Fig. 7.30: Heavy Load R_O Model

Our no load Z_O curve will be computed using the circuit in this Fig. 7.31. From our rule-of-thumb for I_Q vs I_{AB} we would guess that since I_Q=45µA, then I_{AB}=22.5µA for the OPA348. Our error current of 483.65fA should not contribute any significant error for our no load Z_O curve.

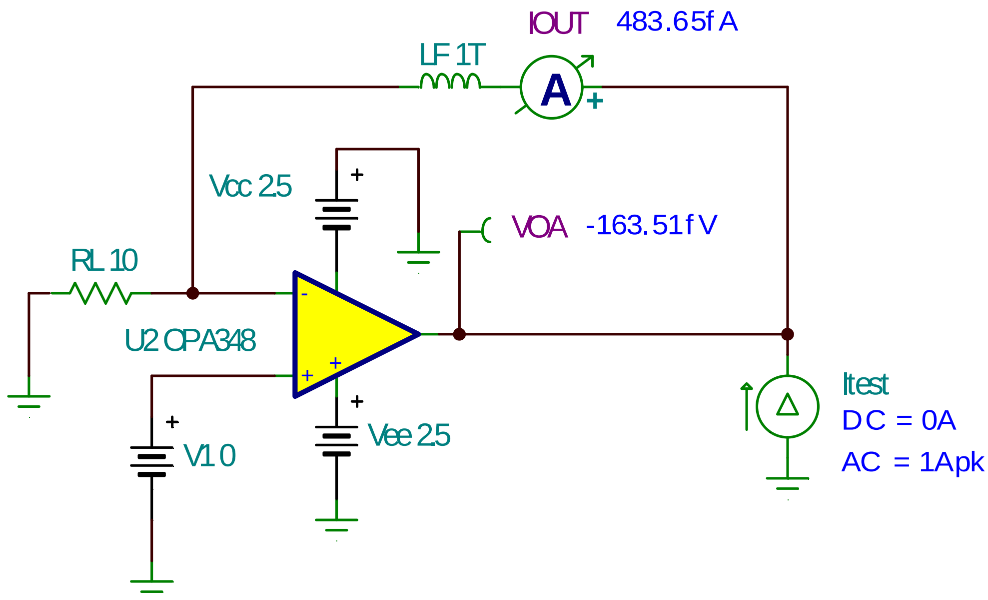


Fig. 7.31: Z_O, No Load, I_{OUT} = 0mA

As shown in Fig. 7.32, for I_{OUT} of 0mA, Z_O has a high frequency R_O component of 196.75Ω. Z_O is clearly capacitive for frequencies lower than about 3kHz.

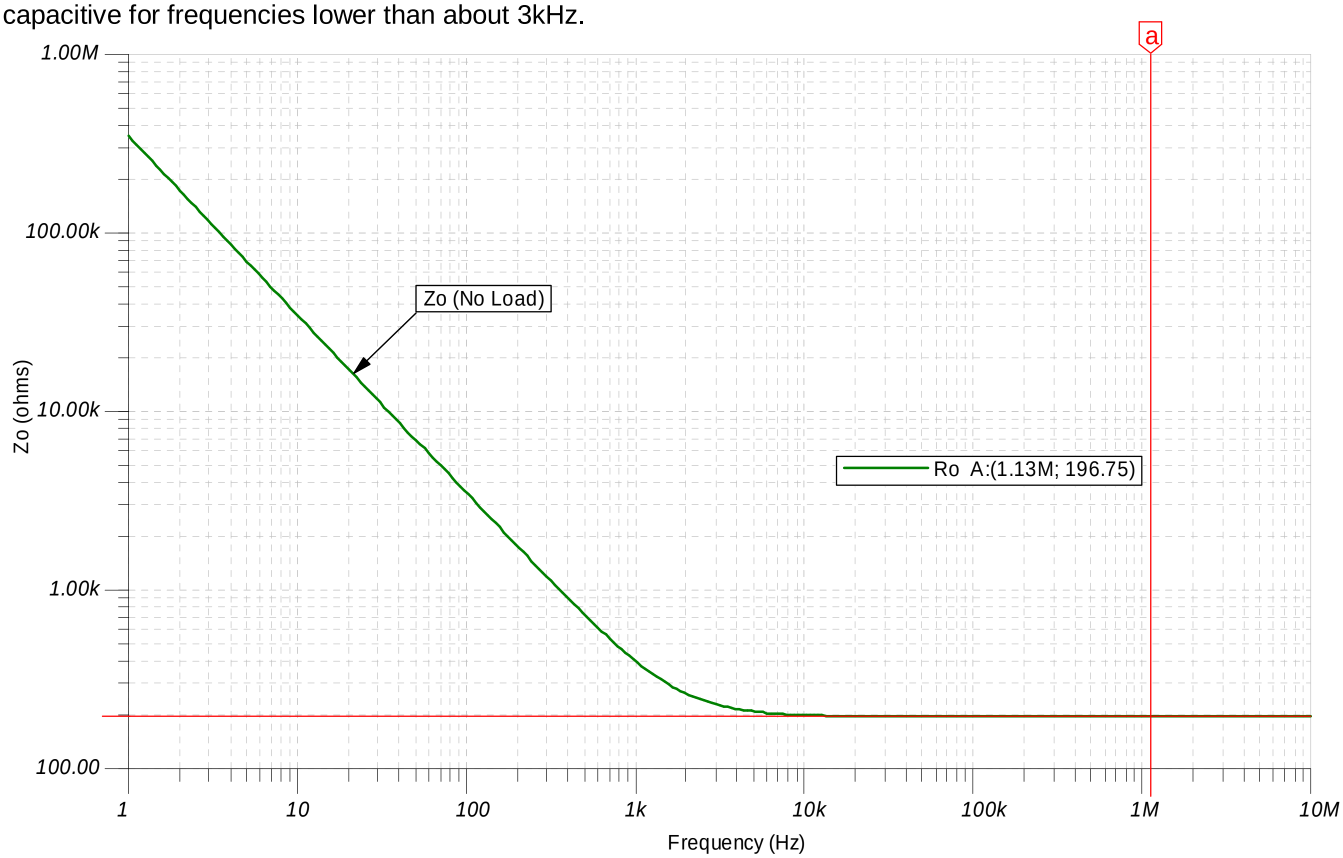
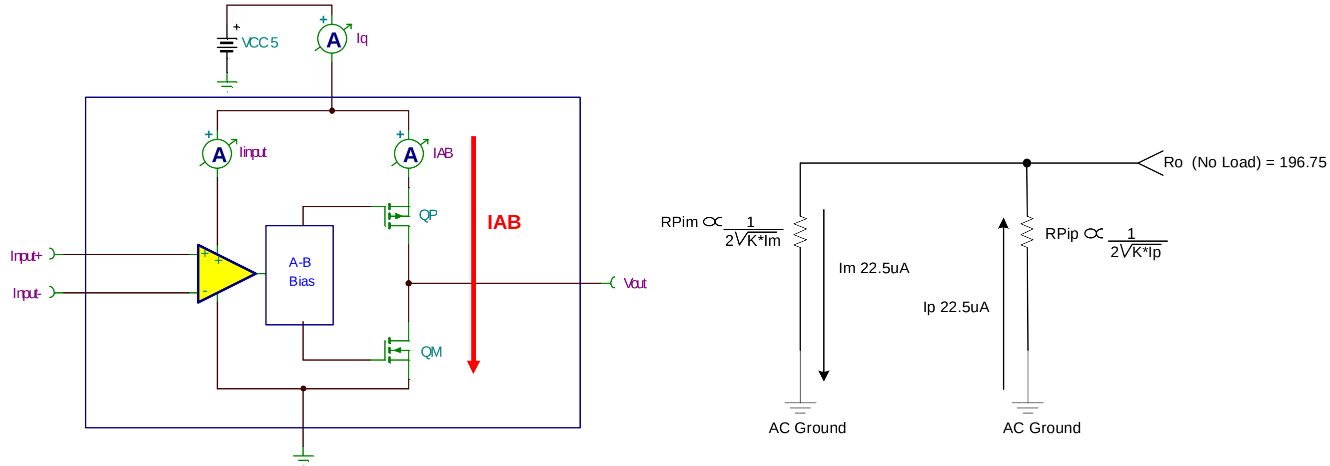


Fig. 7.32: Z_O AC Plot, No Load, I_{OUT} = 0mA

Our no load R_O model in Fig. 7.33 shows that inside the OPA348 both outputs QP and QM are contributing equally to R_O. It also shows an assumed class A-B bias current of 22.5µA.



QP and QM are equally biased on and contribute equally to R_O

Fig. 7.33: No Load R_O Model

We now know what Z_O is for Heavy Load and No Load. The other key curve we are interested in is the light load where R_O becomes the largest value. Since we do not know exactly where this operating point is, because we cannot see inside of the OPA348 class A-B bias stage, we will need to find this point somehow before we compute an AC Transfer curve. If we use the technique and circuit in Fig. 7.34 we can quickly find what we are looking for. If we run the AC Analysis/Calculate AC Nodal Voltages analysis continuously, as shown, we can vary the value of V1 and get an instant update on VOA. VOA will be an rms value reading. We set IG1 to 1A, AC Generator, and f=1MHz (since this is well inside the frequency area where R_O dominates Z_O). Once we find a value for V1 that yields maximum VOA we can use it to run our AC Transfer Curves. Note that VOA is an rms reading which includes any DC component on VOA. Also note for our current levels that this DC value would be down in the 7.35µVrms region which is insignificant when compared to VOA in the 254.56Vrms region. We expect for this light load that the AC magnitude value for R_O will be 254.56Vrms / .707Arms = 360Ω (since for AC sine waves Arms = 0.707Ap).

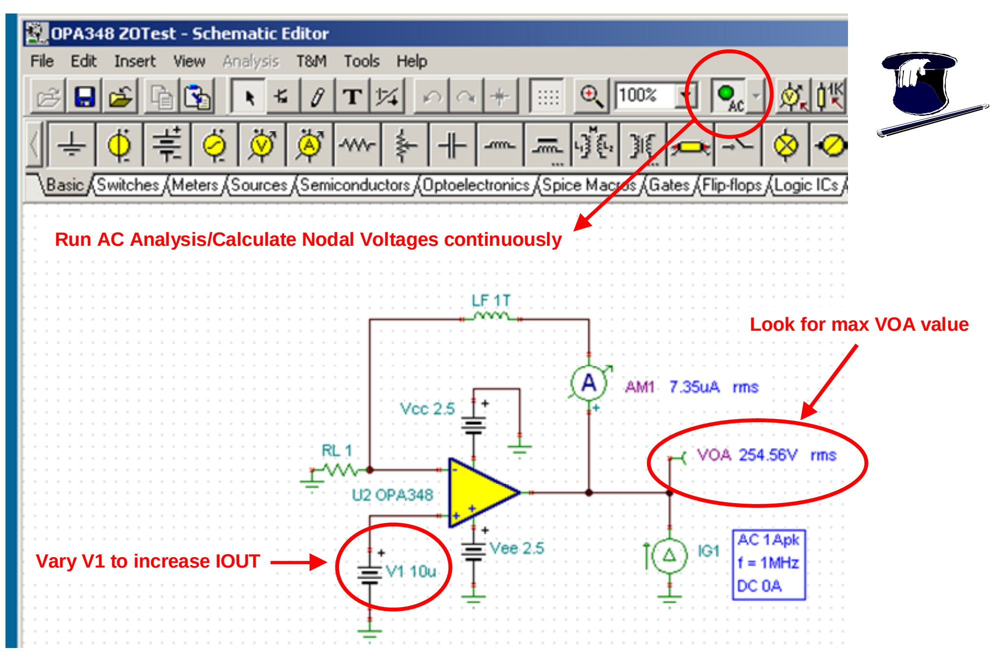


Fig. 7.34: Light Load Search for Max R_O

Our Z_O light load test circuit is shown Fig. 7.35.

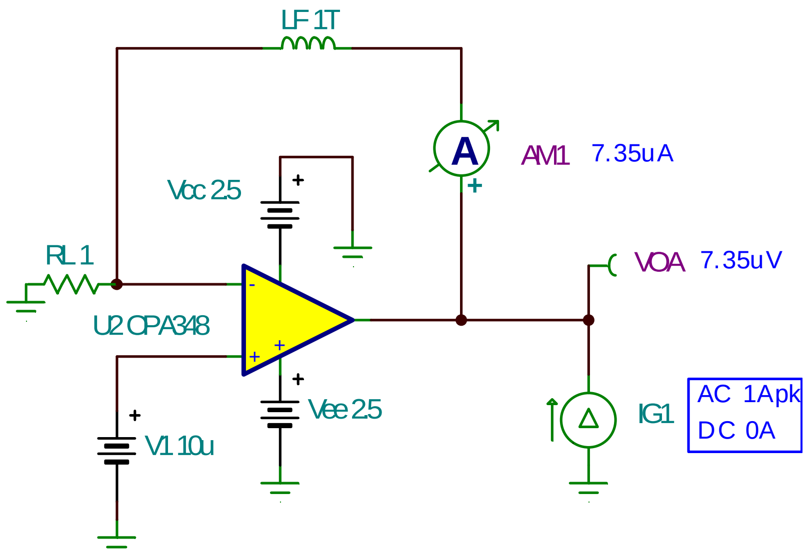


Fig. 7.35: Z_O, Light Load, I_{OUT} = +7.35uA

Results of our Z_O light load AC Transfer function analysis are in Fig. 7.36. We see an R_O value of 360 ohms which is what we had predicted and below about 3kHz Z_O is capacitive.

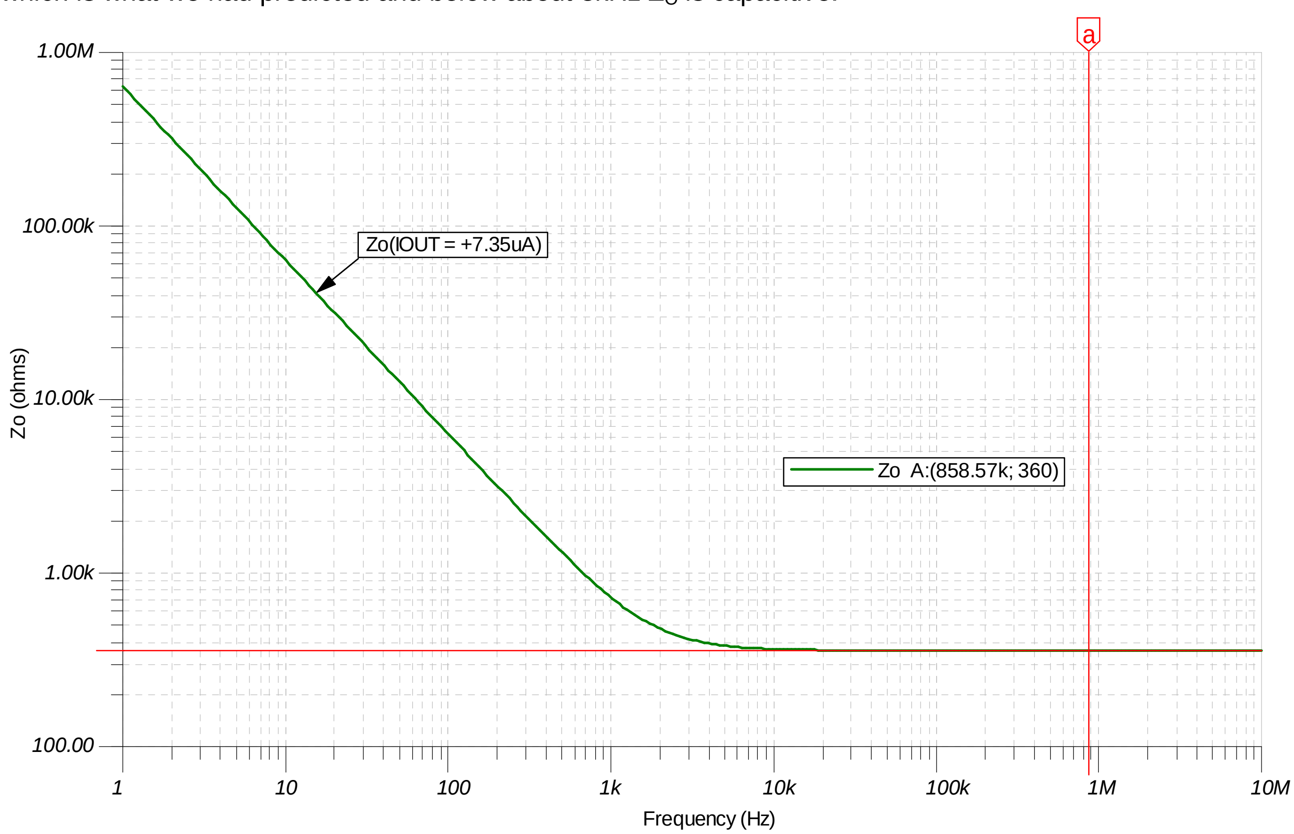
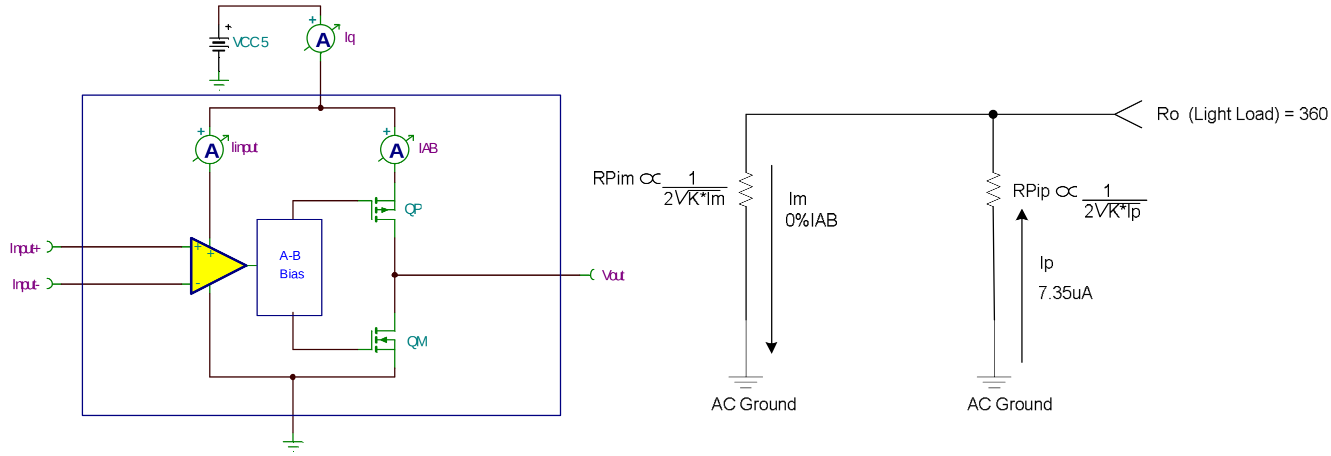


Fig. 7.36: Z_O AC Plot, Light Load, I_{OUT} = +7.35uA

For our light load model (see Fig. 7.37) we see that QP is on and QM is just off and so QP will set the value of R_O since it will be the lowest impedance. We also see that our original assumption of class A-B bias being 22.5µA is probably not correct since it only took 7.35µA of load current to turn off QM. IAB is probably not much greater than 7.35µA.



QP on and QM just off so QP dominates due to lowest impedance

Fig. 7.37: Light Load Z_O Model

Our complete set of Z_O curves for OPA348 are compiled in Fig. 7.38. The Key Curves we are interested in are:
I_{OUT} = +7.35uA (R_O = 360 ohms **à** R_O Max)
I_{OUT} = No Load (R_O = 196.75 ohms **à** R_O No Load)
I_{OUT} = +87.4uA (R_O = 198.85 ohms) I_{OUT} at which R_O about equals R_O No Load.
I_{OUT} > 87.4µA result in R_O < R_O No Load
I_{OUT} = +10mA (R_O = 34.79Ω)

The remaining curves are shown just to verify that operating conditions between these key curves will result in curves which fall between the key curves. In addition Z_O curves were taken for I_{OUT} at negative values of current. But they were so close to laying on top of the I_{OUT} at positive values of current curves they were omitted for clarity. These Key Curves for Z_O should be included in all CMOS RRO op amp data sheets.

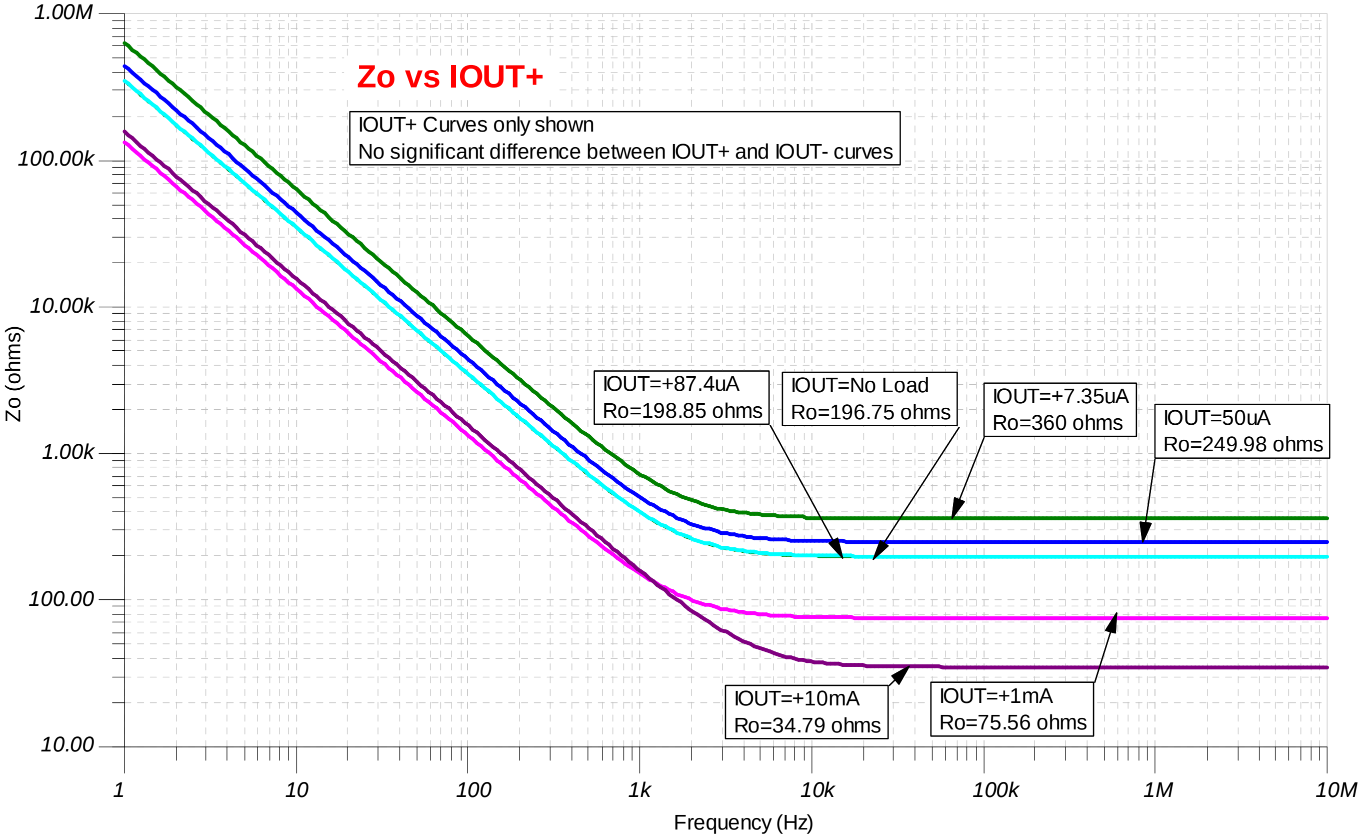


Fig. 7.38: Complete Z_O Curves: CMOS RRO

To build our equivalent Z_O model for RRO CMOS op amps we need to analyze the breakpoint fz on our Z_O curves. For Heavy Load and No Load these breakpoints are measured in Fig. 7.39. This frequency along with the value of R_O will allow us to determine a value for CO.

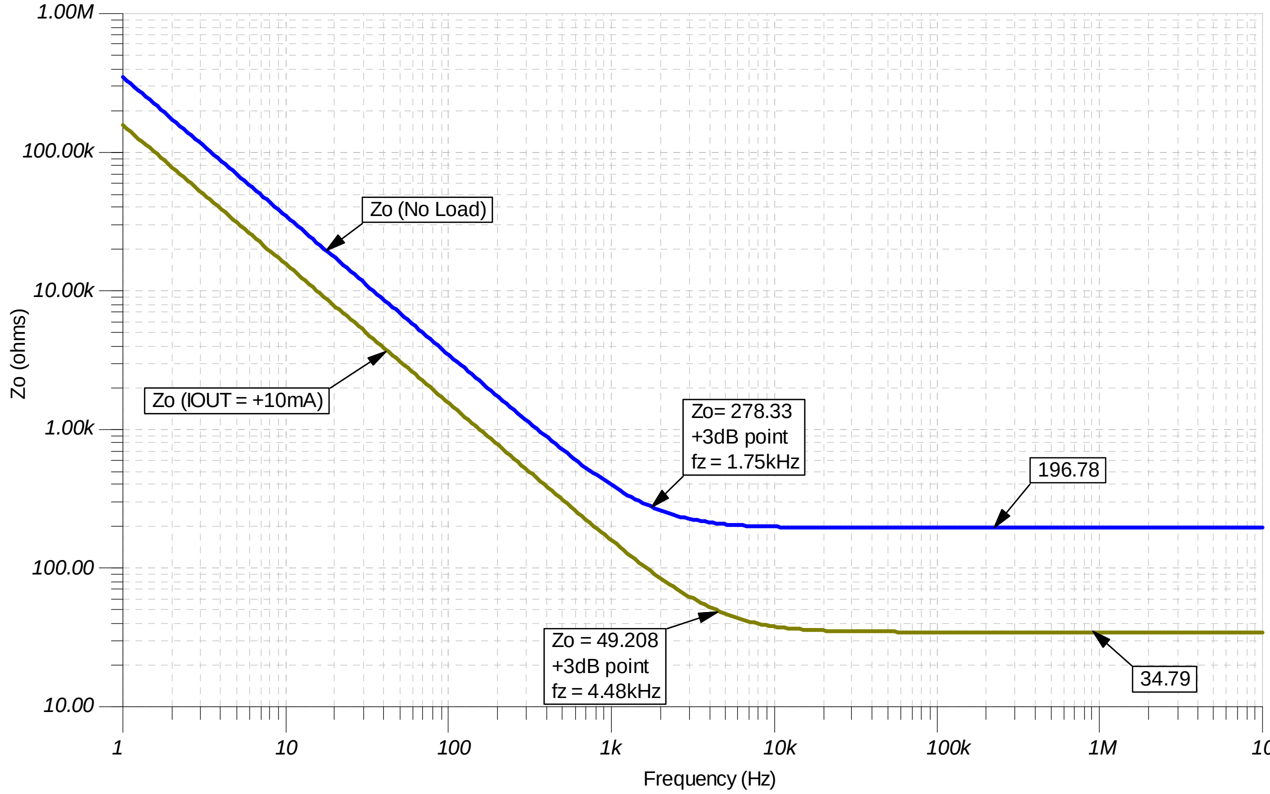
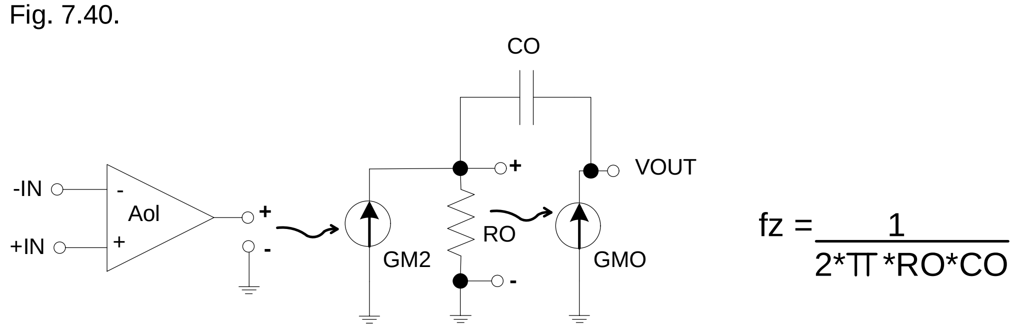


Fig. 7.39: fz Breakpoints on Z_O Curves

From our Z_O plots we can now complete our model for Z_O at the given I_{OUT} loads of No Load and Heavy Load (10mA) in Fig. 7.40.

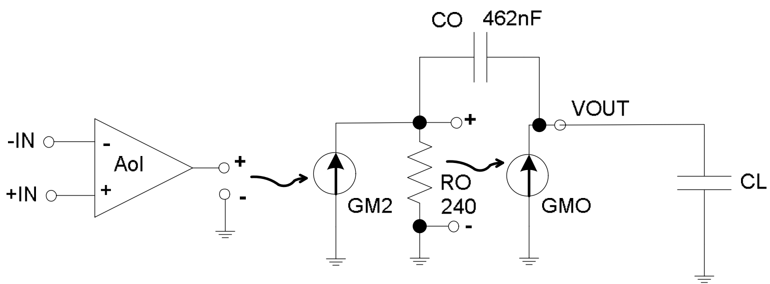


	fz	RO	CO
No Load	1.75kHz	196.78 ohms	0.4622uF
Heavy Load	4.48kHz	34.79 ohms	1.0211uF

Fig. 7.40: Z_O Complete Model Calculations

Z_O and Capacitive Loads for CMOS RRO Op Amps

For creating modified Aol curves from the original op amp Aol, when we are driving capacitive loads, the load capacitor, CL, will be in series with our Z_O model capacitor, CO. Remember that capacitors in series are like resistors in parallel. And so, if CL < CO, CL will dominated and then if CL > CO, CO will dominate. The modified Aol curve second pole, fp2, will depend directly on R_O and Ceq, the equivalent capacitance due to CO and CL. Fig. 7.41 illustrates these key points.



$$fp2 = \frac{1}{2*\pi*Ceq*RO}$$

CL<462nF CL dominates: Ceq $\approx$ CL

CL>462nF CO dominates: Ceq $\approx$ CO

$$\text{where: } Ceq = \frac{CO * CL}{CO + CL}$$

remember:

1) capacitors in series are like resistors in parallel
2) XC = 1/sC
3) XCeq = 1/sCO +1/sCL
4) Ceq = 1/XCeq

Fig. 7.41: Modified Aol fp2 Calculations

Our test circuit to plot modified Aol curves due to capacitive loading on the CMOS RRO op amp, OPA348 is shown in Fig. 7.42. The AC loop is opened by LT which provides a short for the DC operating Point calculation. CT is open for DC but shorted for any AC frequency of interest. The modified Aol curve will be VOA / VM.

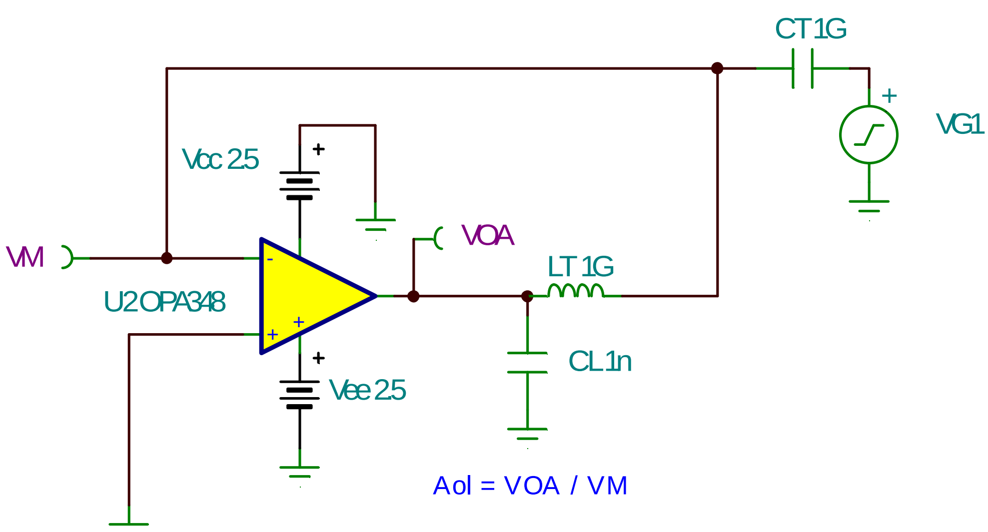


Fig. 7.42: Modified Aol Test Circuit

Our actual modified Aol curves for CL from No Load to 10,000nF are seen in Fig. 7.43. The respective locations of fp2 were measured as noted.

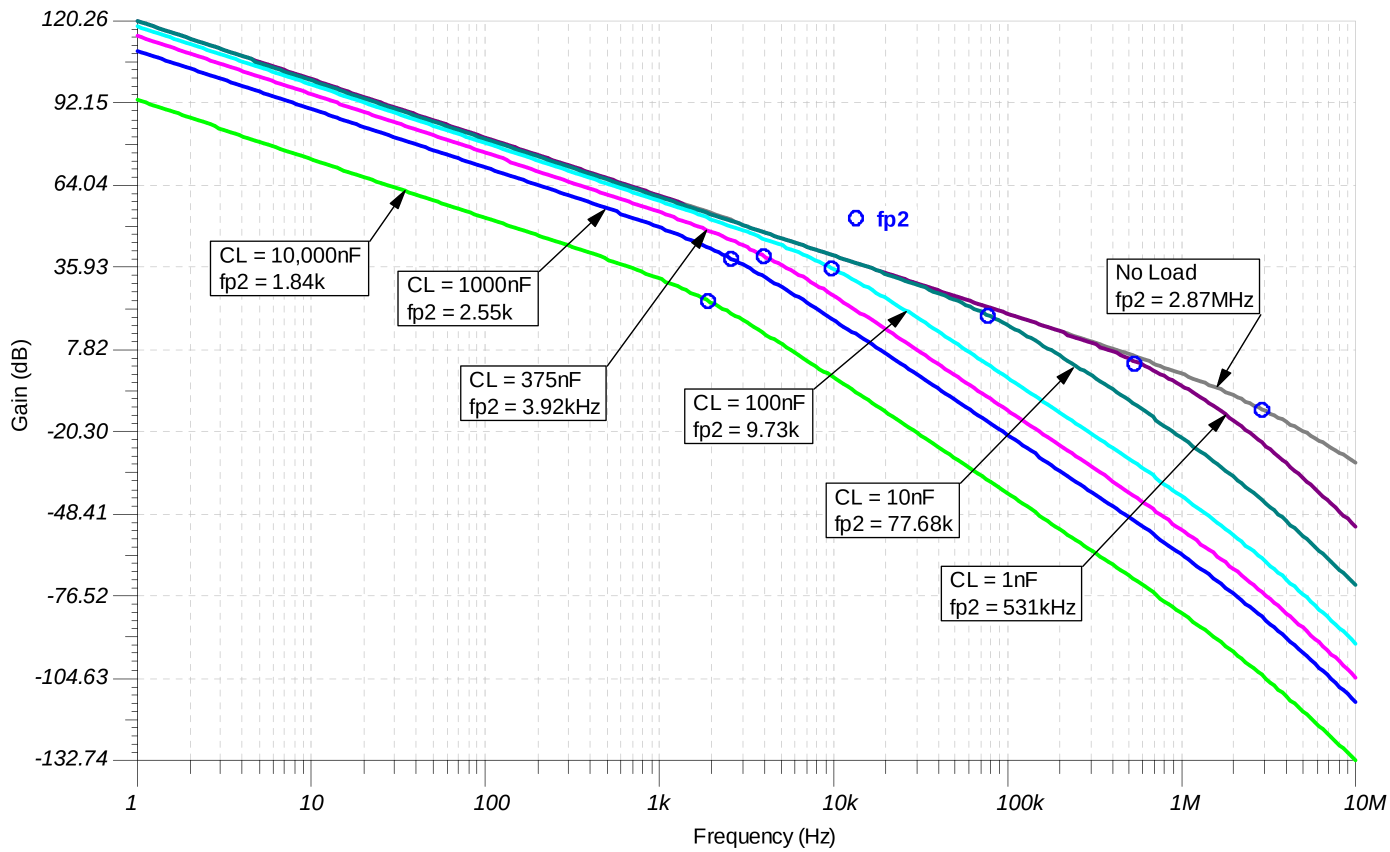


Fig. 7.43: Modified Aol Curves Due to CL

Now the measured values of fp2 were compared to the predicted values form our Z_O model, in Fig. 7.44. Results are very good giving us the confidence to use our Z_O model to predict actual modified Aol plots. Note the 1nF load predicted was off quite a bit due to the fact that we did not include the effect of the OPA348 Aol's second high frequency pole at 2.87MHz. The other fp2 locations due to CL were at least a decade away from 2.87MHz and so the OPA348 Aol second pole has no effect on our predictions.

RO	196.78				
CO	4.62E-07				
RL	No Load				
				Predicted	**Actual**
CL	**CL**	**CO**	**Ceq**	**fp2**	**fp2**
	(farads)	(farads)	(farads)	(Hz)	(Hz)
No load	No Load	4.62E-07			2870000
1nF	1.00E-09	4.62E-07	9.98E-10	810546	*531000
10nF	1.00E-08	4.62E-07	9.79E-09	82630	77680
100nF	1.00E-07	4.62E-07	8.22E-08	9838	9730
375nF	3.75E-07	4.62E-07	2.07E-07	3907	3920
1000nF	1.00E-06	4.62E-07	3.16E-07	2559	2550
10,000nF	1.00E-05	4.62E-07	4.42E-07	1831	1840

*Actual reflects effect of Op Amp Aol second pole

Fig. 7.44: Modified Aol fp2 Comparison: Predicted vs Actual

Low Frequency Effects of RL on CMOS RRO Op AMP Aol

Just when we thought we were done with CMOS RRO op amps…. CMOS RRO op amps also exhibit another Aol phenomena at low frequencies. The interaction of CO with RL creates a high pass filter effect which tends to flatten the low frequency portion of the Aol curve as shown in Fig. 7.45.

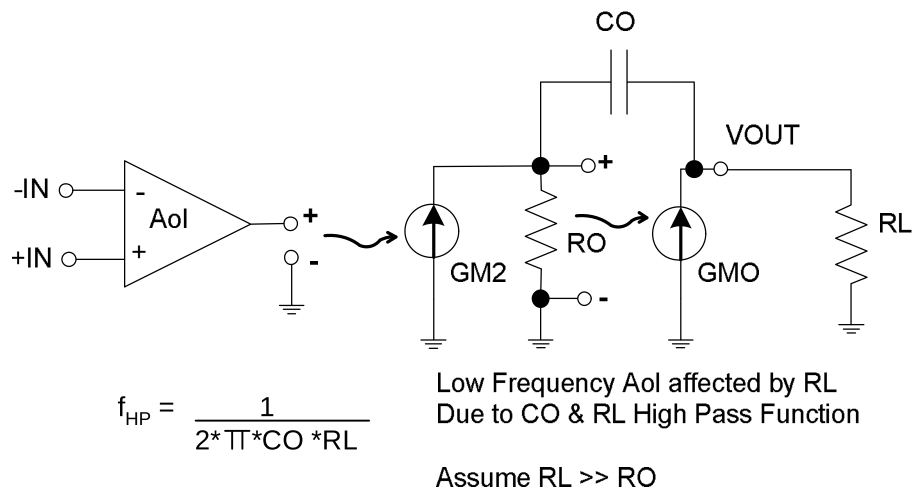


Fig. 7.45: Aol Low Frequency Effects of RL

Our test circuit for analyzing the effects of RL on the CMOS RRO Aol curve is in Fig. 7.46. RL can easily be varied to see the effects on Aol.

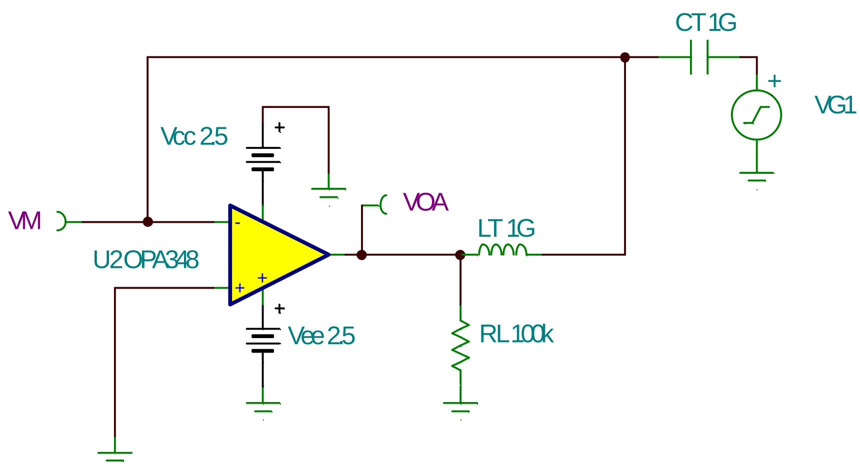


Fig. 7.46: Aol Low Frequency Effects of RL Test Circuit

Fig. 7.47 clearly shows the low frequency Aol effects due to a resistive loading of No Load, 100kΩ, and 5kΩ.

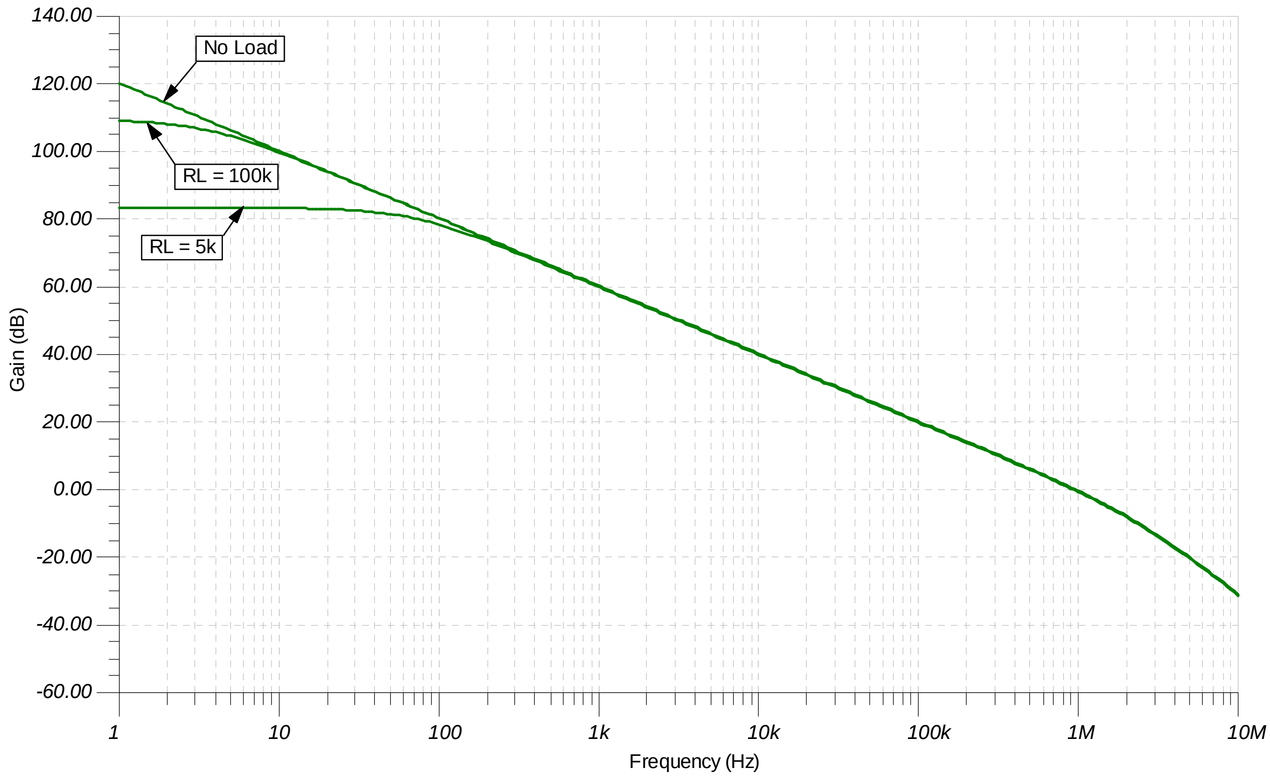


Fig. 7.47: AC Plot of RL Effects on Low Frequency Portion of Aol

A clever test circuit in Fig. 7.48 will allow us to see clearly the effects of CO and RL on the low frequency portion of the CMOS RRO Aol curve. Vaol represents the unloaded, unmodified Aol curve. VHP is the high pass filter function created by CO and RL. VOA is the modified Aol curve caused by passing the unmodified Aol curve thought the high pass filter formed by CO and RL.

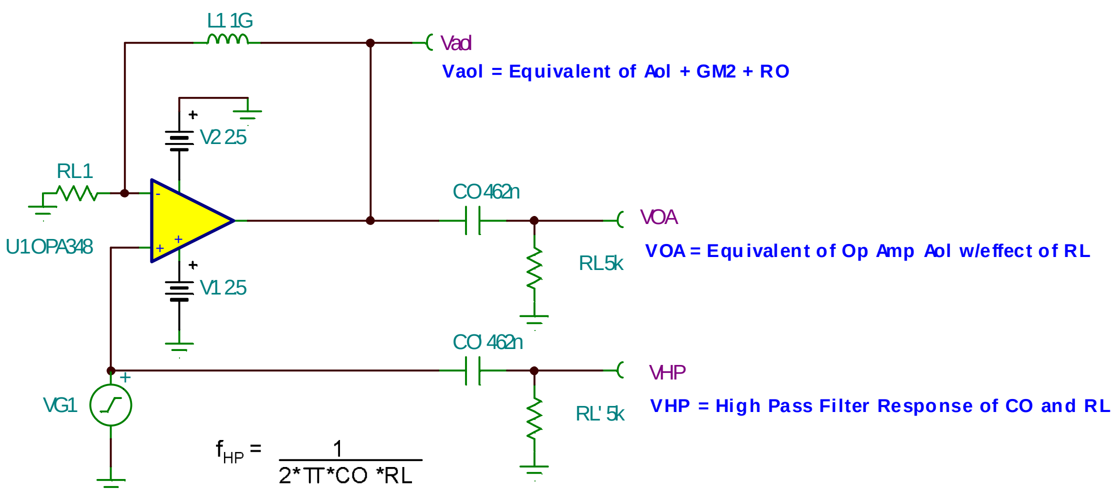


Fig. 7.48: Equivalent Circuit to Evaluate RL Effects on Aol

For RL=5kΩ our resultant AC curves in Fig. 7.49 show the unmodified Aol curve, Vaol, the high-pass filter effect due to CO and RL, and the net transfer function, modified Aol curve VOA due to passing Vaol through VHP. Since addition on a Bode plot is equivalent to linear multiplication we can easily add Vaol to VHP to see the resultant VOA curve.

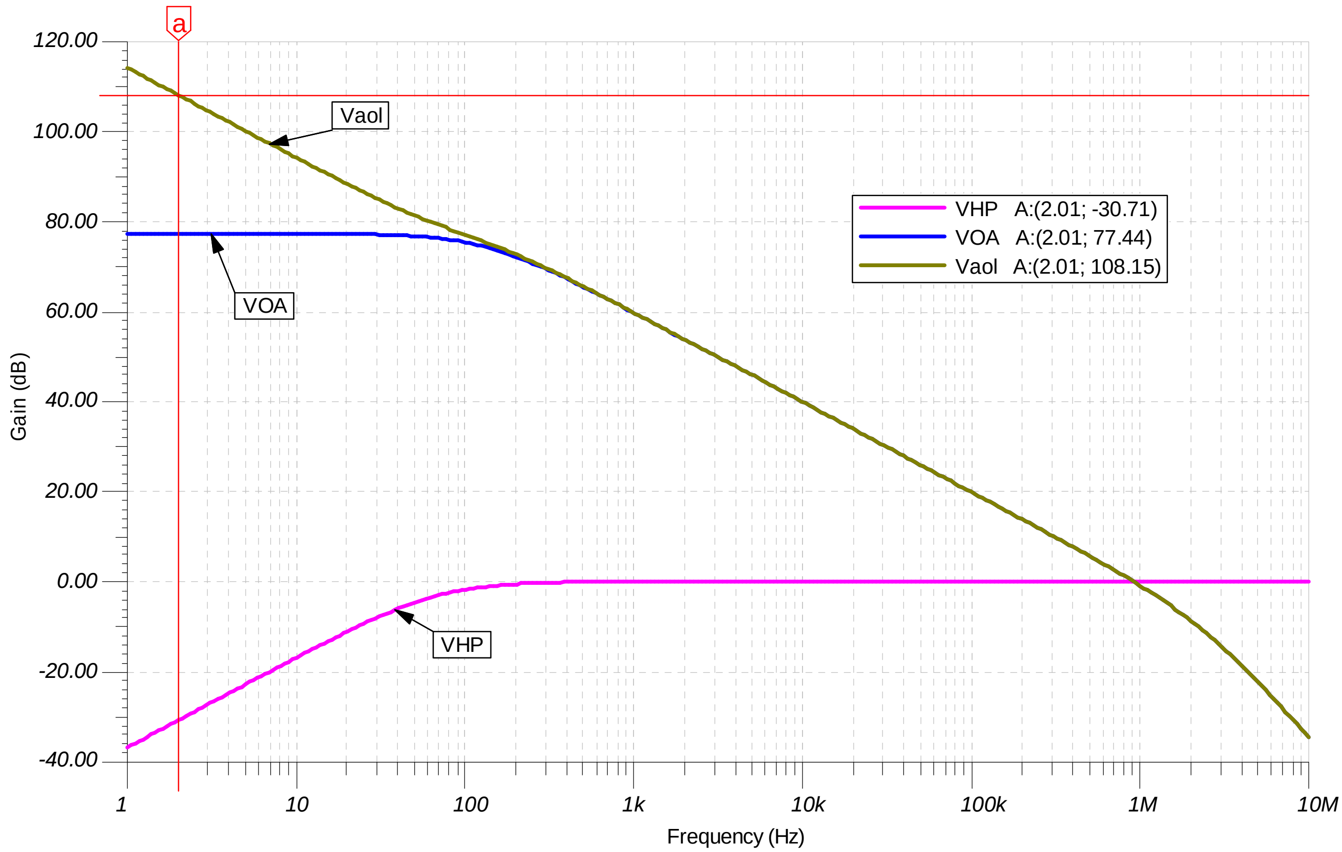


Fig. 7.49: Equivalent Circuit Plots to Evaluate RL Effects on Aol

Z_O **Summary for CMOS RRO Op Amps**

Fig. 7.50 summarizes the key characteristics of Z_O for CMOS RRO op amps. At high frequencies Z_O is dominated by R_O. For most loads, as DC output load current increases R_O decreases making R_O inversely proportional to I_{OUT}. However, for low values of I_{OUT}, R_O is proportional to I_{OUT}. Z_O is capacitive, CO, at mid to low frequencies. If capacitive loads, CL, are connected to a CMOS RRO output then R_O and CO will interact with CL to create a modified Aol curve which contains an additional pole, fp2, from the original Aol curve. The low frequency portion of the Aol curve is affected by resistive loads, RL, interacting with CO, forming a high pass filter function and flattening the Aol curve in the mid to low frequency region. R_O does change with process and temperature. A good rule-of-thumb for this change which includes process and temperature changes is 0. 5*$R_O$typ at -55C to 2*$R_O$typ at 125C, where $R_O$typ is the 25C typical value for R_O. There are always exceptions to the rules-of-thumb we have developed for open loop output impedance of CMOS RRO op amps. The most complete and accurate data for Z_O should be obtained from the op amp manufacturer or measured.

ØZ_O is Dominated by R_O at High Frequencies

ØR_O is Inversely Proportional to I_{OUT} for Most Values of I_{OUT}

ØR_O is Proportional to I_{OUT} for Very Small Values of I_{OUT}

ØZ_O is Capacitive (CO) at Mid to Low Frequencies

ØR_O, C_O, and CL form a Second Pole to create a Modified Aol

ØRL and C_O change the Low Frequency Portion of Aol

ØR_O Change with Process and Temperature:

- **ü R_O @ -55C = 0.5 * $R_O$typ (i.e. 50 ohms)**
- **ü R_O @ 25C = $R_O$typ (i.e. 100 ohms)**
- **ü R_O @ +125C = 2 * $R_O$typ (i.e. 200 ohms)**

ØUse $R_O$typ for Stability Synthesis

- **ü Decade Rules-of-Thumb will provide Design Margin**

Fig. 7.50: Z_O Summary for CMOS RRO

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Tony Larson, Senior Analog IC Design Engineer
Rod Burt, Senior Analog IC Design Manager

Analog & RF Models
Bill Sands, Consultant
(http://www.home.earthlink.net/%7Ewksands/)

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Holt, Charles A. *Electronic Circuits.* John Wiley & Sons. New York. 1978

About the Author
After earning a BSEE from the University of Arizona, Tim Green has worked as an analog and mixed signal board/system level design engineer for over 24 years, including brushless motor control, aircraft jet engine control, missile systems, power op amps, data acquisition systems, and CCD cameras. Tim's recent experience includes analog & mixed-signal semiconductor strategic marketing. He is currently the Linear Applications Engineering Manager at Burr-Brown, a division of Texas Instruments, in Tucson, AZ.