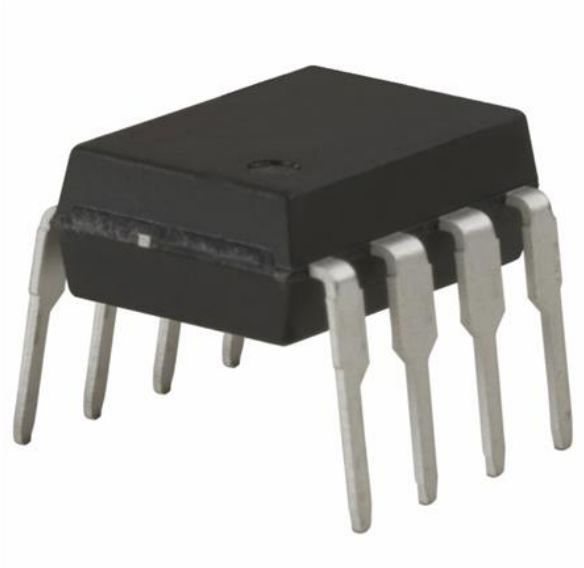
Operational Amplifier Measurements with Bode100



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Note: Basic procedures such as setting-up, adjusting and calibrating the Bode 100 are described in the Bode 100 user manual. You can download the Bode 100 user manual at www.omicron-lab.com/bode-100/downloads#3

Note: All measurements in this application note have been performed with the Bode Analyzer Suite V2.41 SR1. Use this version or a higher version to perform the measurements shown in this document. You can download the latest version at www.omicron-lab.com/bode-100/downloads

1 Executive Summary

This application note explains how to measure the open loop gain & phase of an operational amplifier. When an amplifier circuit is designed it is important to know the poles of the used operational amplifier. Also the transit frequency and the Gain-Bandwidth-Product are of importance for a working design.

2 Measurement tasks

Before creating a circuit with an operational amplifier it is very helpful to know its exact electric behavior. Bode 100 offers several possibilities for the verification of operational amplifiers circuits.

By analyzing operational amplifiers the following questions are answered:

1. How to measure the open loop gain & phase of an OpAmp?
2. Does the open loop gain & phase correspond with the theoretical values described in the datasheet?
3. Where are the poles of the examined operational amplifier?
4. What is the DC-Amplification of the examined Op-Amp?

3 Measurement Setup & Results

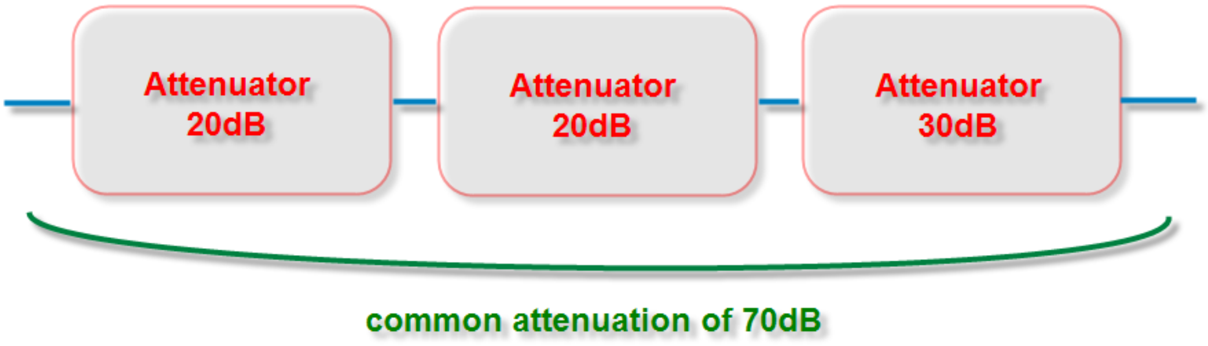
3.1 Used Equipment

Beside the Bode 100 the following equipment was used to perform the measurements described in this application note:

- Vector Network Analyzer Bode 100 (with its measurement accessories)
- Attenuators (in total 70dB)
- Filter Feedback Network
- Oscilloscope (not necessarily required, but helpful)
- Power supply (for the OP-AMP circuit)
- OP-AMP circuit (e.g. on a development board)

3.1.1 70dB Attenuator:

To get an attenuation of 70dB we did connect a 30dB and two 20dB attenuators in series. The frequency range of the used attenuators is from DC to 4GHz.



3.1.2 Power supply:

We powered our Op-Amp circuit with ±15V (symmetric) from a laboratory power supply.

If a higher measurement range than 10MHz is required, it might necessary to use additional ceramic capacitors at the output of the supply to block distortions.

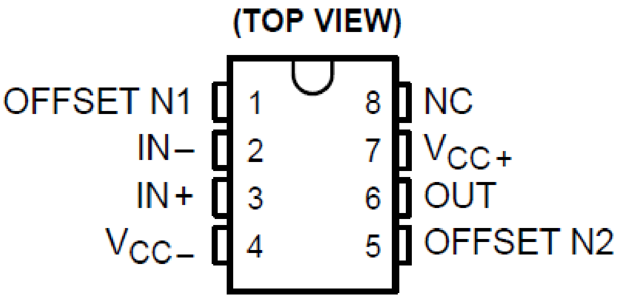
3.1.3 Oscilloscope:

For this application note an oscilloscope is not absolutely necessary. But it becomes quite handy to control if the output signal remains sinusoidal and that it is not limited by the supply current. Maximum peak output voltage swing should not exceed ±2V to keep harmonic distortions low. To measure the output voltage, connect the oscilloscope in parallel to CH2 of the Bode 100.

3.1.4 OP-AMP parameters:

For the measurements a TL081 (JFET-Input Operational Amplifier) was used. Here are the most important parameters of the from the data sheet of the TL08x series:

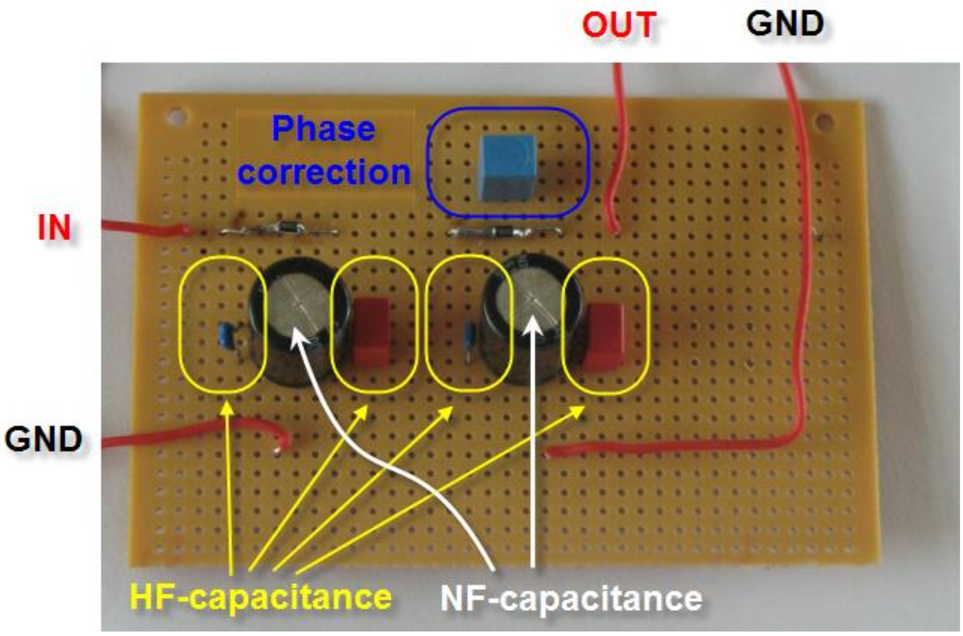
- Manufacturer: Texas Instruments
- Type: TL081CP
- Transit frequency 3MHz
- Open loop gain: 200 V/mV (~106dB)
- Input offset voltage: 3mV
- Supply voltage: ±15V
- Pin assignment: see below



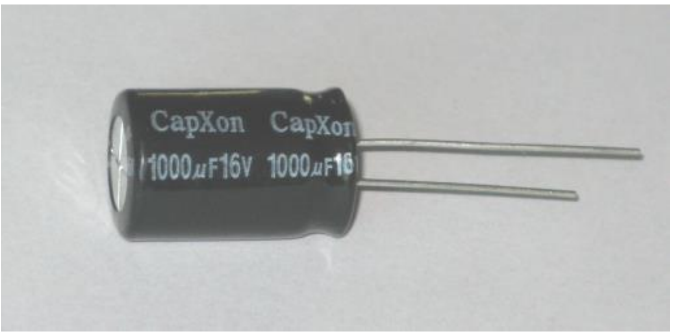
Pin	Name	Function
1	OFFSET N1	Offset adjustment pin1 (NC in our Application)
2	IN-	Inverting input
3	IN+	Non-inverting input
4	VCC-	Negative power supply (-15V)
5	OFFSET N2	Offset adjustment pin2 (NC in our Application)
6	OUT	Output
7	VCC+	Positive power supply (+15V)
8	NC	NC…Not connected

3.1.5 Feedback network:

The use and design of the feedback network will be explained later. It is a 2.Order low pass with a phase correction. The feedback network was built on a test print. There are additional capacitances for the higher frequencies beside the low frequency capacitance.



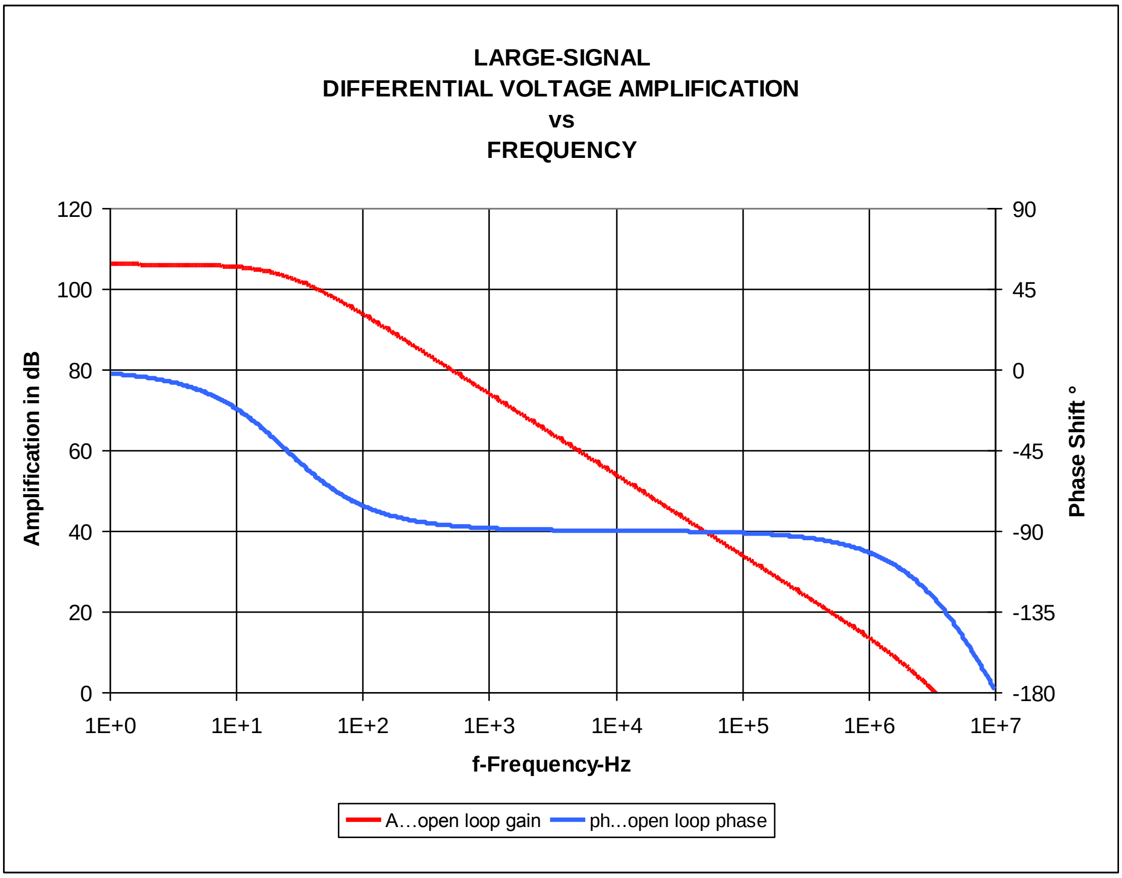
Note: The used NF-Capacitors are bipolar electrolytic capacitors. Normal (unipolar) electrolytic capacitors might not work.



3.2 Theoretical information open loop gain & phase of Op-Amps

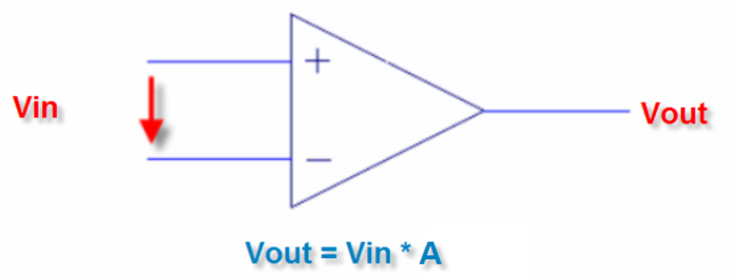
An ideal operational amplifier has an amplification of A=∞ at every frequency. In reality OP-AMPs have only an amplification of approximately V=106 over a small frequency range from

DC – 10Hz (caused by the internal design of an OP-AMP). In the following picture we can see an open loop gain & phase of the used OP-AMP (TL081):



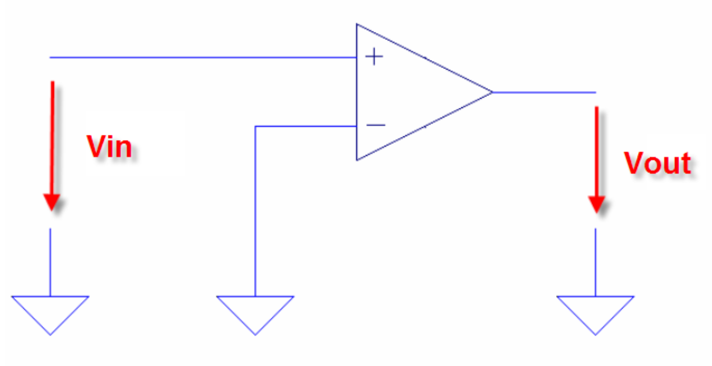
3.2.1 Definition of the open loop gain & phase:

The output voltage U_a is defined by U_{in}*A (U_{in}…input voltage; A…open loop gain). An OP-AMP has an inverting and non-inverting input. The input voltage is defined as the voltage difference between the inverting and non-inverting input as shown in the picture below.

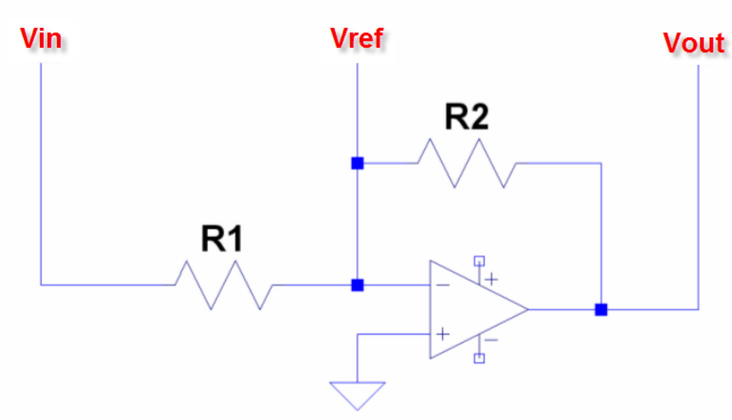


3.3 Simplified Measurement of the open loop gain & phase:

To measure the open loop gain & phase we set the inverting input to ground. The non-inverting input voltage U_{in} and output voltage U_a are related to ground.



The problem with this measurement setup is that offset drifts (e.g. caused by temperature variations) are amplified with a gain of ~ 10^6. So if the offset voltage is e.g. 1mV, the output would be limited by the supply voltage (~ 14V). Therefore it is necessary to eliminate the offset with a feedback network which is illustrated in the next point. For the following measurements we chose a standard inverting op-amp circuit as shown below.



The chosen resistor values are R_1=10 kΩ and for R_2=110 kΩ.
The supply voltage is ±15V.

$$\frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}$$

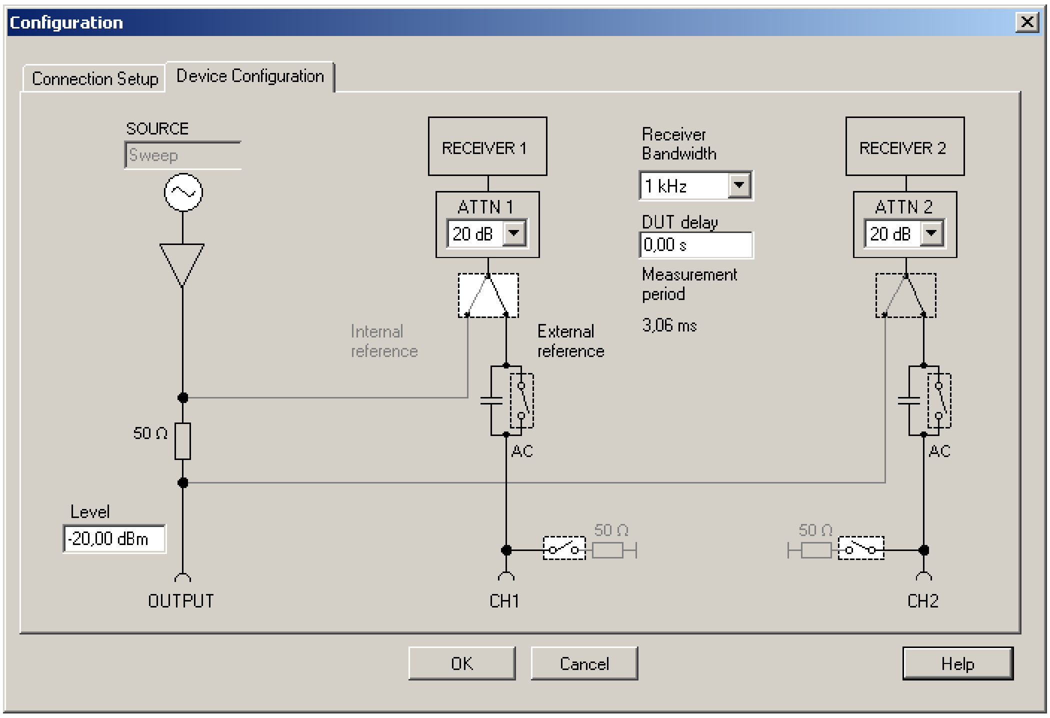
The circuit has a gain of –11 which means that the output voltage is 11 times the input voltage. The minus in front of the gain shows that the output voltage is 180° phase shifted in comparison to the input voltage.

3.3.1 Measurement setup:

For the measurement of the open loop gain we are using the inverting op-amp circuit.

Please set-up your Bode 100 as follows:

- Mode: Frequency Sweep
- f(min) 10 Hz
- f(max) 1 MHz (depends on your op-amp → data sheet)
- Reference external
- Attn CH1 & CH2: 20 dB
- Receiver Bandwidth: 1 kHz
- DUT delay. 0 s
- Number of points: 201
- Impedance CH1 & CH2: high
- Source Level: -20 dBm
- Sweep mode: logarithmic

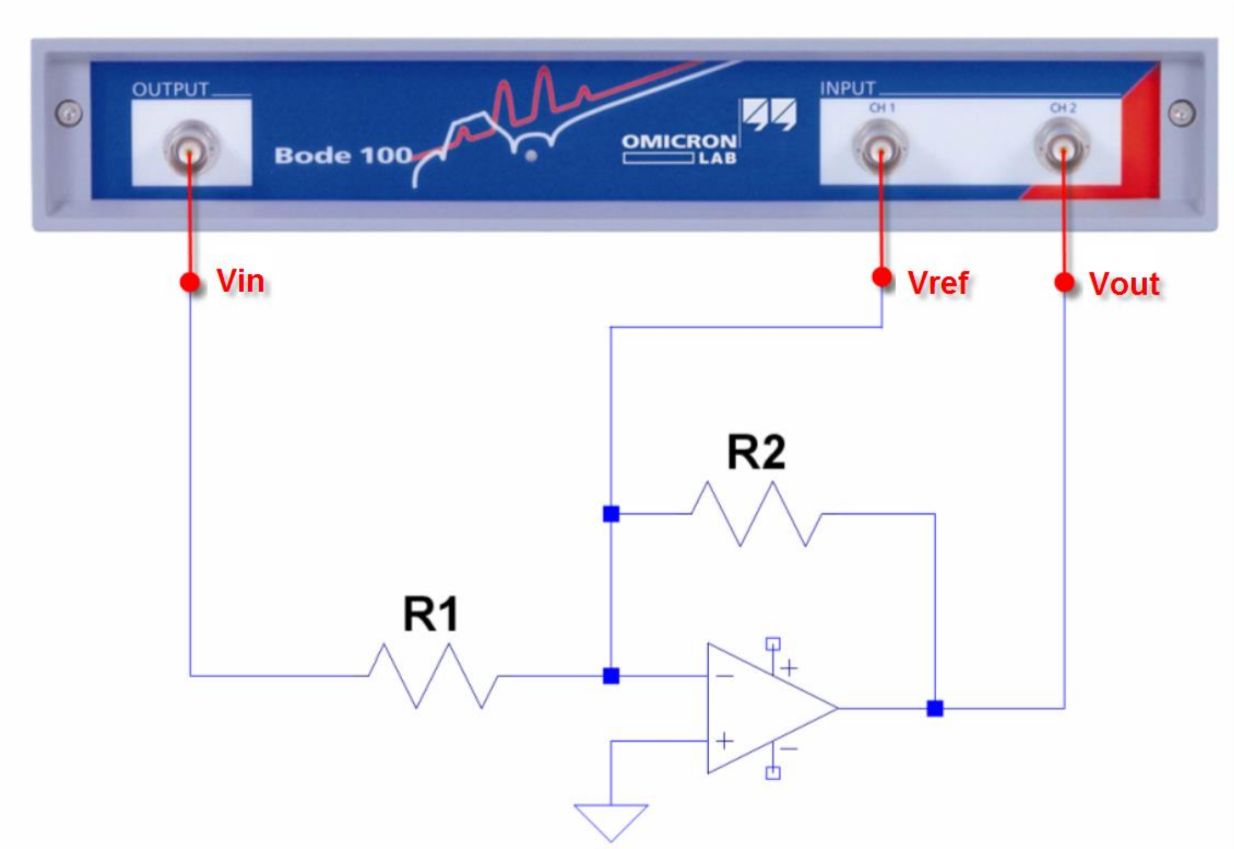


Note: To minimize the influence of the cables used to connect the circuit to Bode 100 it is advisable to perform a THRU calibration as shown in the manual in the section "Calibration in the Gain/Phase mode (CH1 reference)"

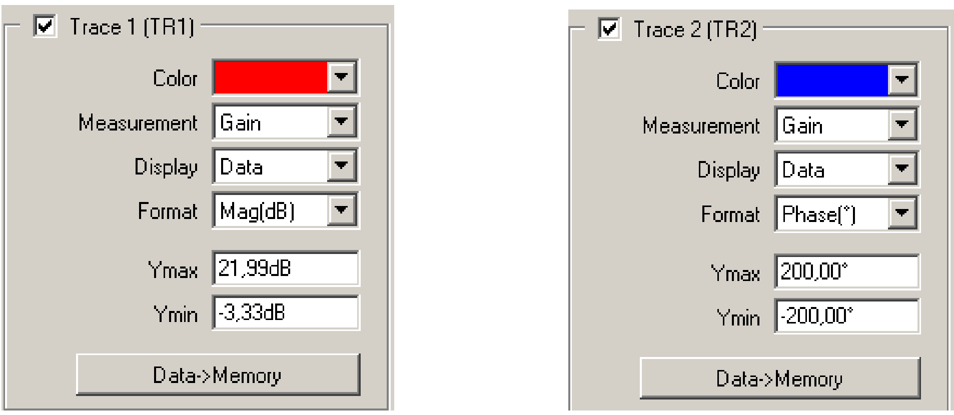
- Connect Bode 100's output to the input (V_{in}) of your circuit.

- Connect Bode 100's input CH1 is to the inverting input (V_{ref}) of your op-amp.

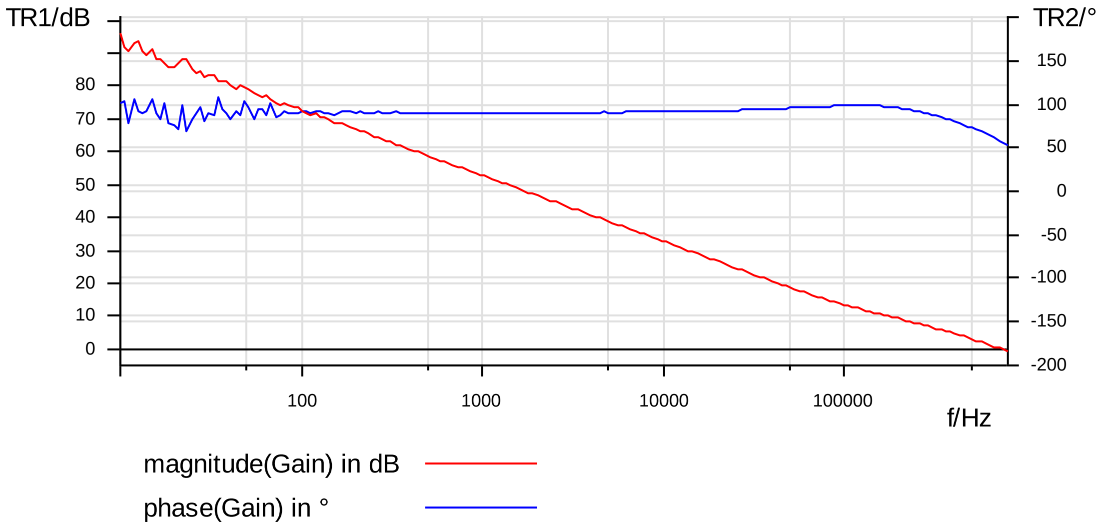
- Connect Bode100's input channel CH2 to the output (V_a) of your circuit.



- Activate Trace 1 to measure the open loop gain & phase and Trace 2 to measure the phase response as shown below:



- Now start the sweep measurement to record your frequency response curve.



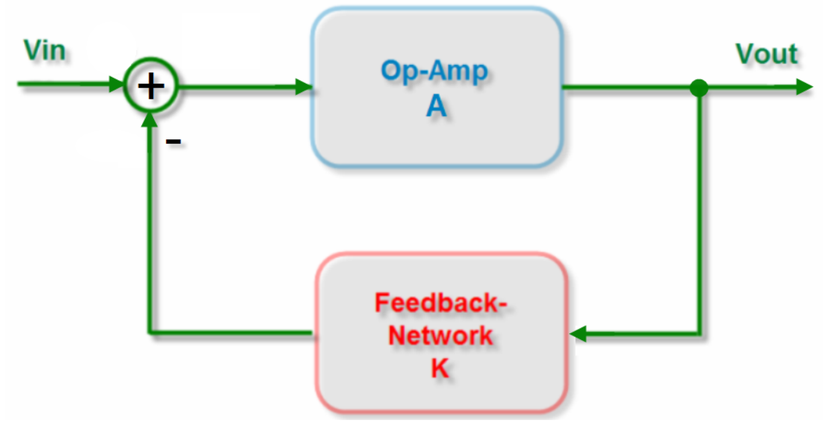
As we can see from the frequency response curve, the amplification at low frequencies is "noisy". This effect results from the small reference voltage connected to CH1. It is too small to measure the real open loop gain & phase at low frequencies.

The conclusion is that we need another measurement method to measure the open loop gain & phase. Therefore we created a more sophisticated method which is described in the next section.

3.4 Advanced measurement of the open loop gain & phase

3.4.1 Idea of the new measurement method:

The aim of our new method is to eliminate the effects caused by offset voltage, while still being able to measure the open loop gain in a range between 1 Hz and 40 MHz. To reach this goal we add a feedback network.



The common transfer function: $$\frac{V_{out}}{V_{in}} = \frac{A}{1+K*A}$$

Specifications for the open loop gain & phase measurement:

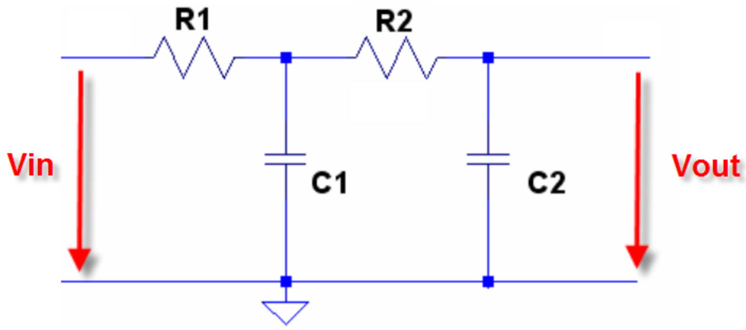
Frequency <<1Hz

$$\frac{V_{out}}{V_{in}} = 1$$

Frequency >1Hz

$$\frac{V_{out}}{V_{in}} = A$$

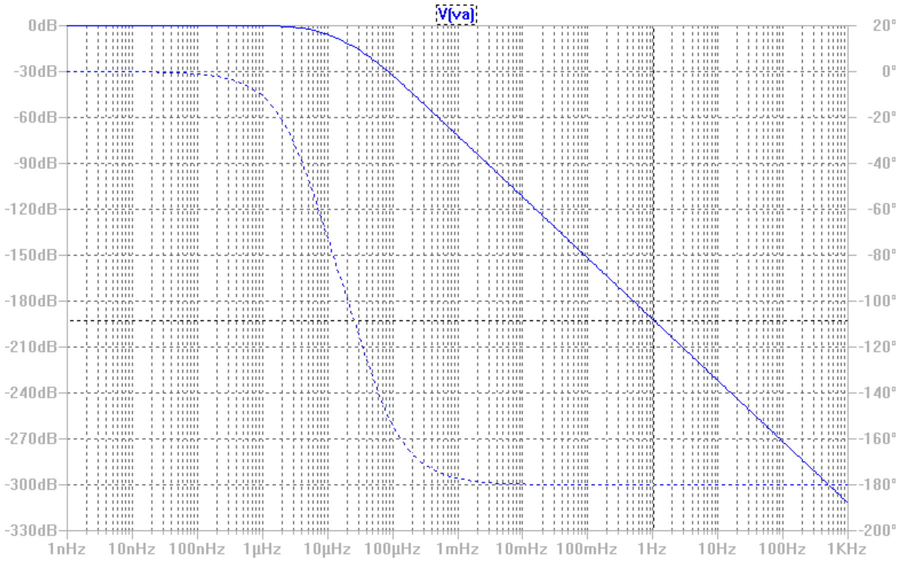
Low frequency signals should be attenuated while signals with frequencies >1Hz should be amplified with A. A low pass filter achieves such a behavior. We have chosen a 2nd order low pass filter built up as a simple resistor-capacitance combination.



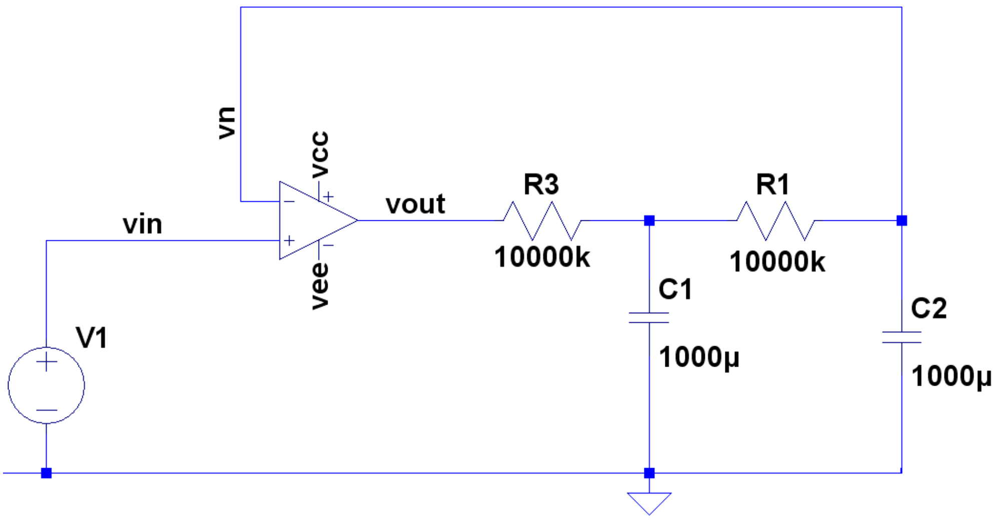
The cut-off frequency is set to 10-5 Hz. So with an attenuation of 40dB/decade we have at least an attenuation of 120dB at 10-2 Hz. After 10-2 Hz the gain follows the open loop gain. We have chosen following values for the feedback network.

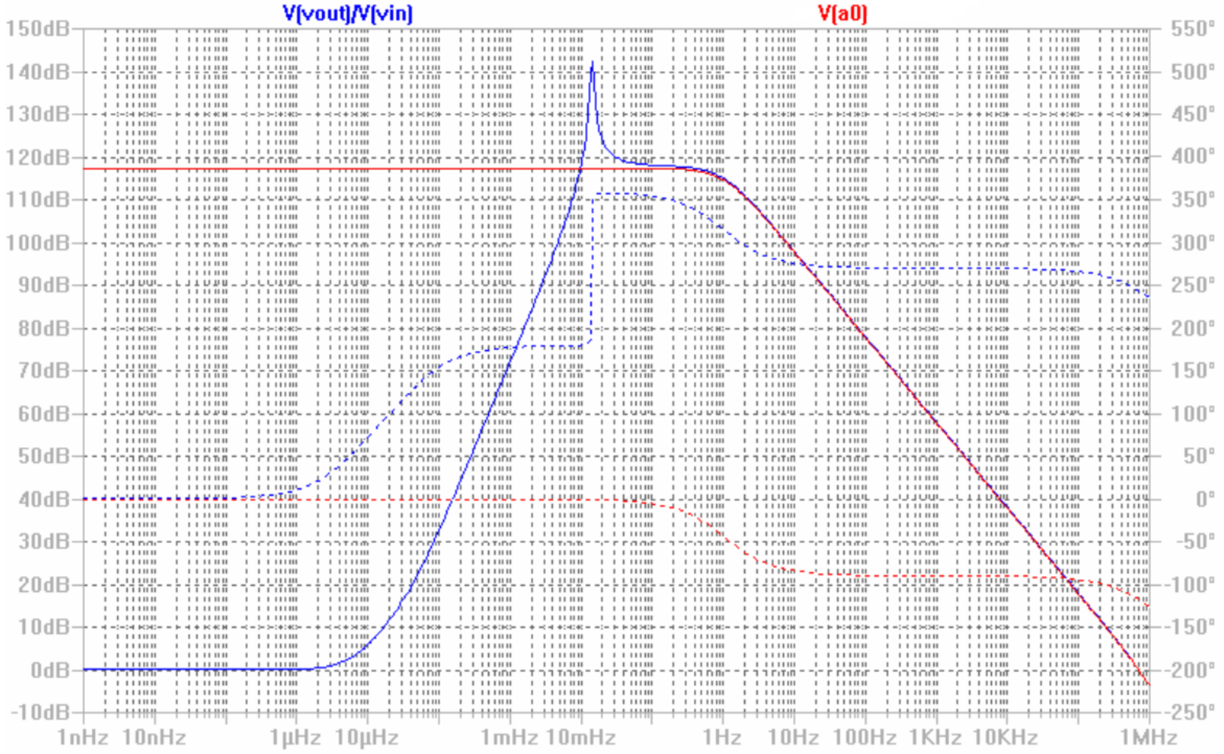
R1=R2=10MΩ
C1=C2=1000µF (bipolar aluminum electrolytic capacitance)

In the graph below the simulated transfer function of the filter is shown.



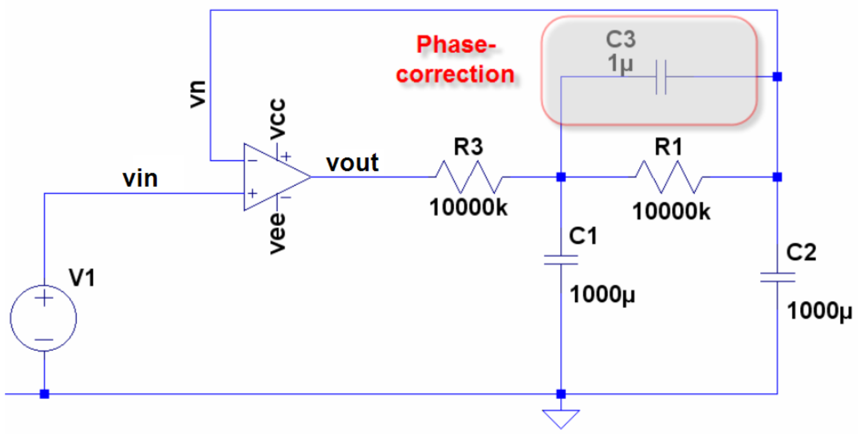
Now we can add the feedback network to the OP-AMP and simulate the whole system.

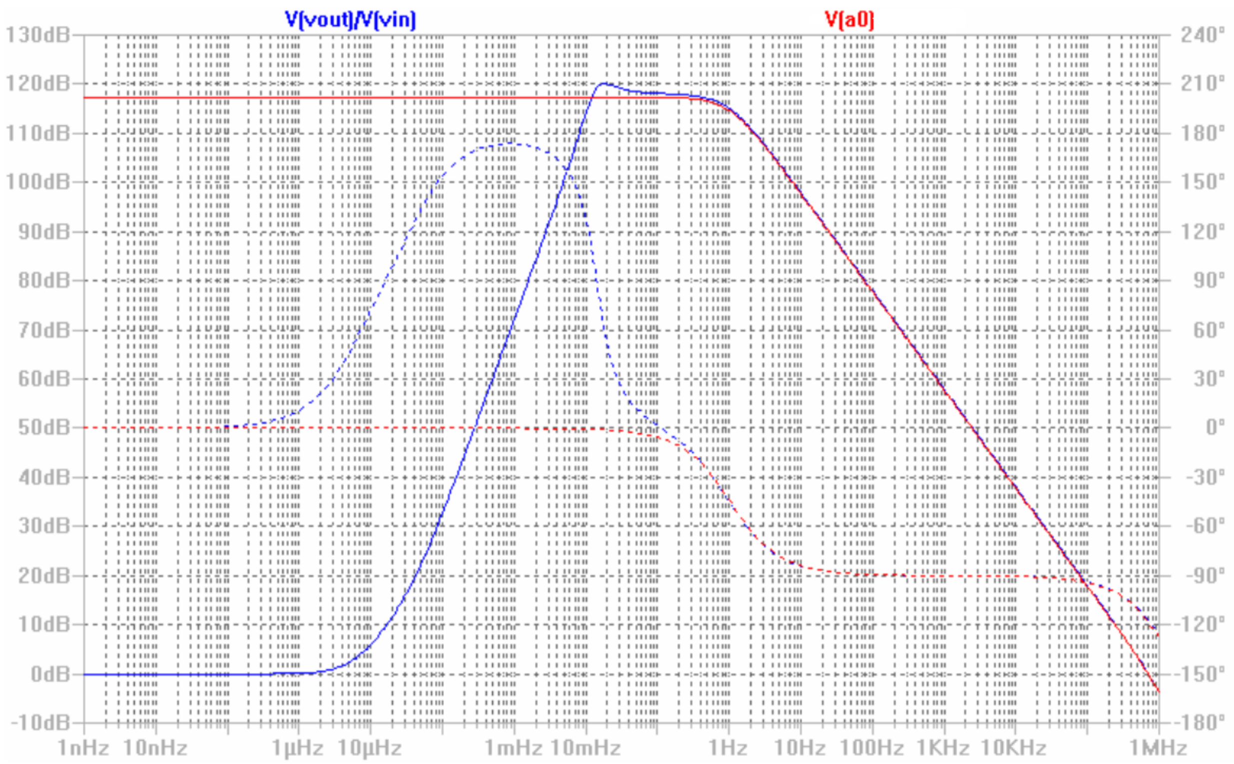




The above diagram shows the open loop gain of the OpAmp (red curve) and theoretical measurement result for the described circuit (blue curve).

We can see that at approximately 10 mHz a phase shift of 180° is present. The system will be oscillating at this frequency. To avoid this phase shift an additional capacitance as shown in the following picture is added.



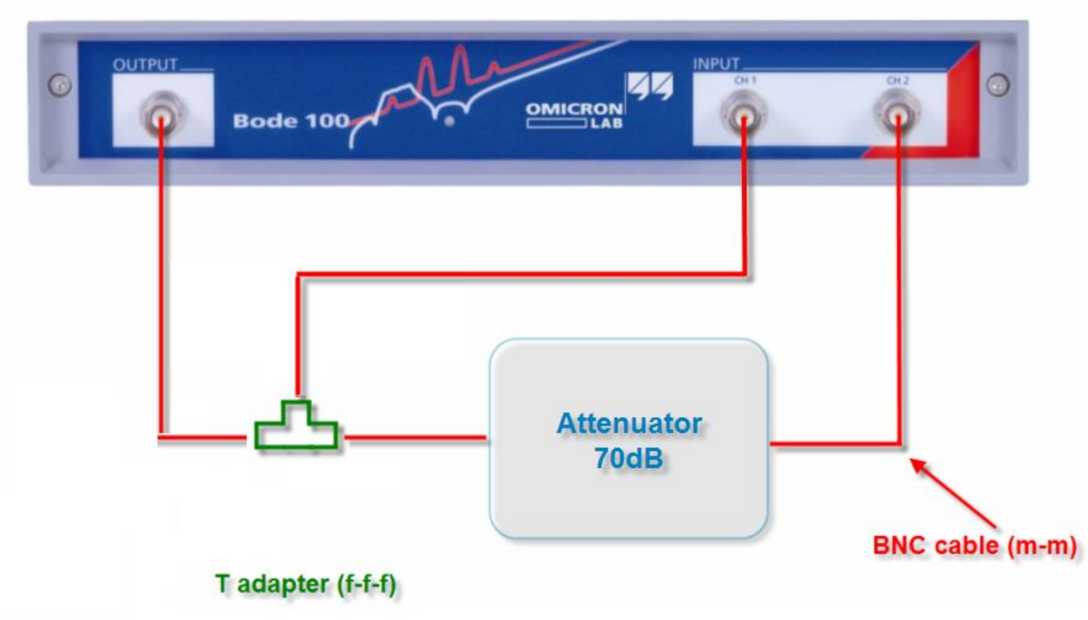


By adding the additional capacitor C3 the 180° phase shift can be avoided and a stable performance of the circuit can be reached. The resulting phase error at 1Hz (simulation) is lower than 1°.

Therefore this circuit seems to be adequate to measure the open loop gain & phase of the TL081 in a frequency range from 1Hz – 40 MHz.

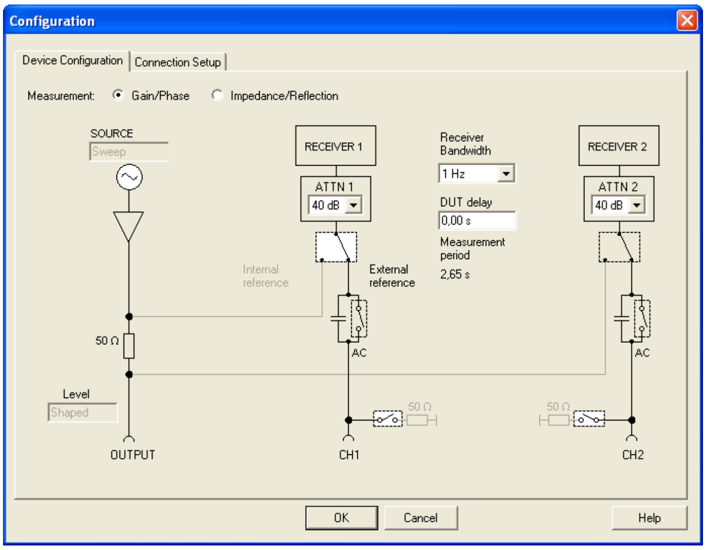
3.4.2 Measurement setup:

With this measurement setup it is possible to measure the open loop gain & phase with Bode 100. Due to the high amplification of the Op-Amp it is required to add an attenuator in front of the input. Connect the Bode 100 as shown and follow the points.

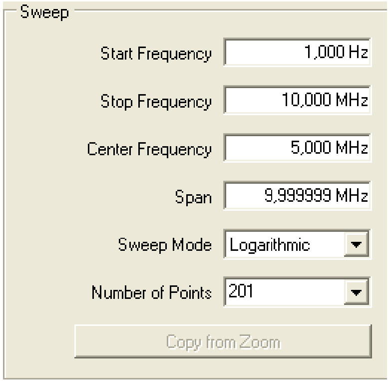


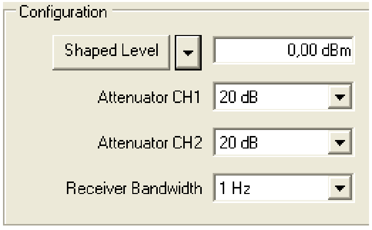
- Select the "Frequency Sweep" Mode

- Configure Bode 100 as shown

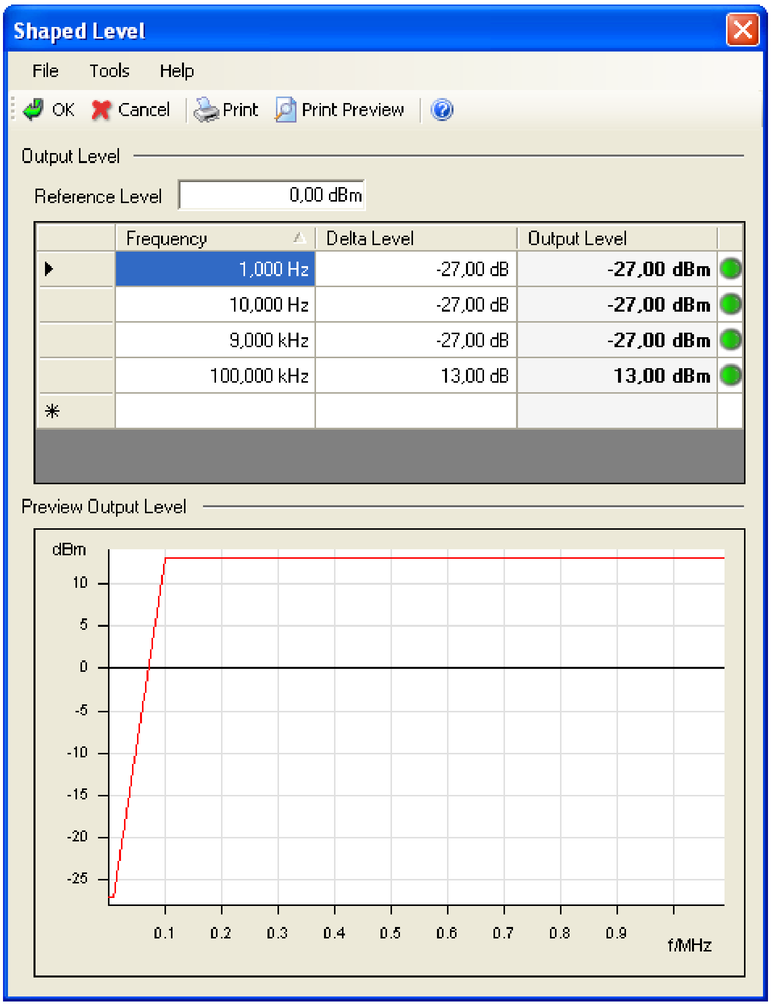


- Also set the sweep configuration.





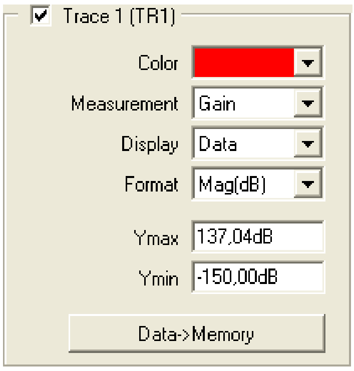
For a higher dynamic range it is necessary to define a level shape for the output. Set the shaped level as shown (see Bode 100-User Manual – Chapter Level Shaping).

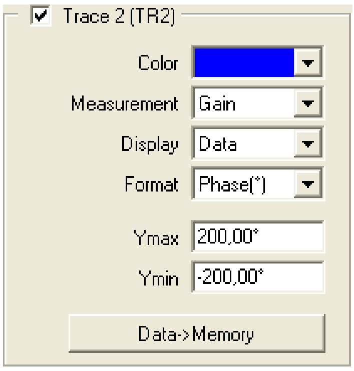


- To ensure your measurement success, calibrate the Bode 100 (User- Calibration/Gain-Phase) which is shown in the Bode 100-User Manual in the section *Calibrating Bode 100.*

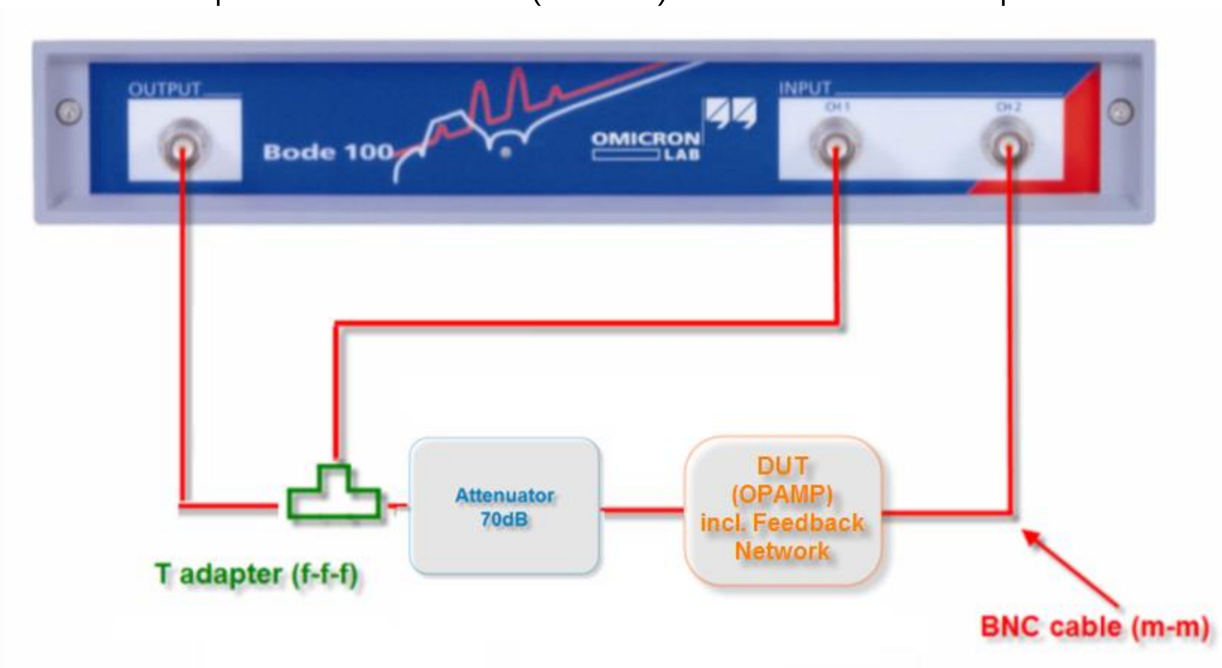
3.4.3 Measurement of the open loop gain & phase:

Before the measurement is started please set the display-settings as shown.

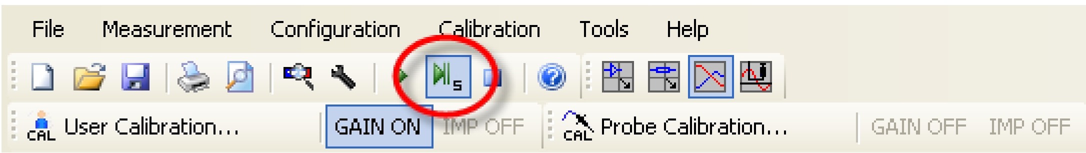




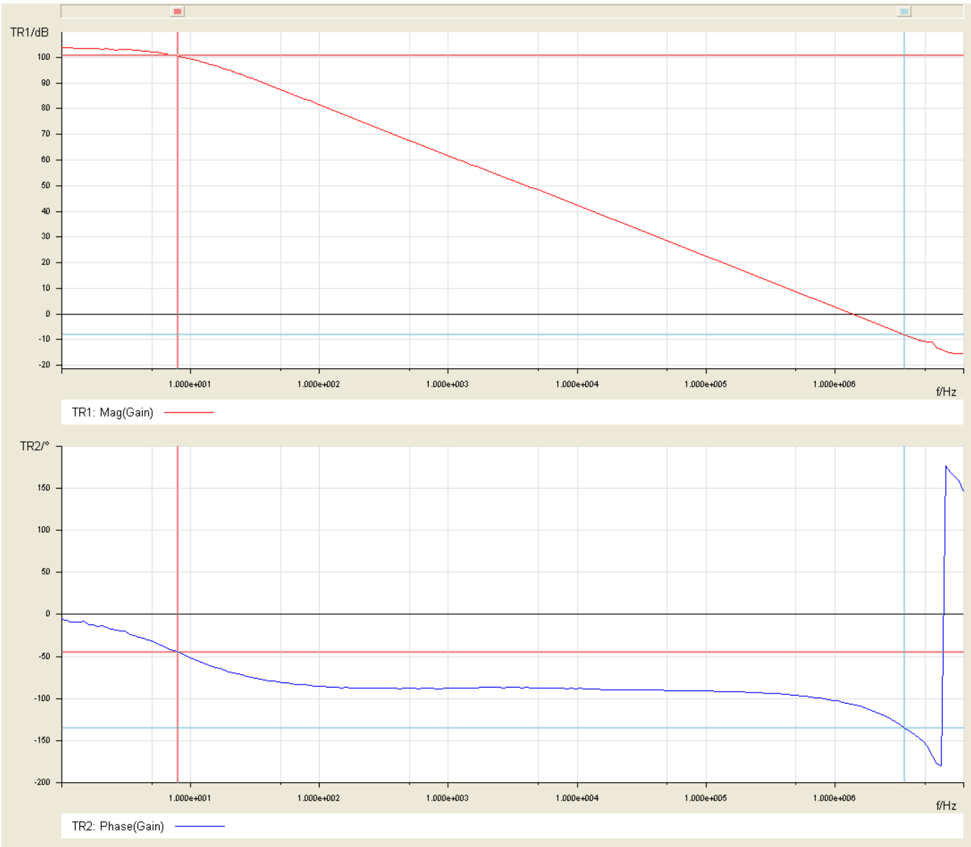
- The next step is to connect the DUT (OP-AMP) to our measurement setup.



- Now press the "single measurement button" and start the measurement.

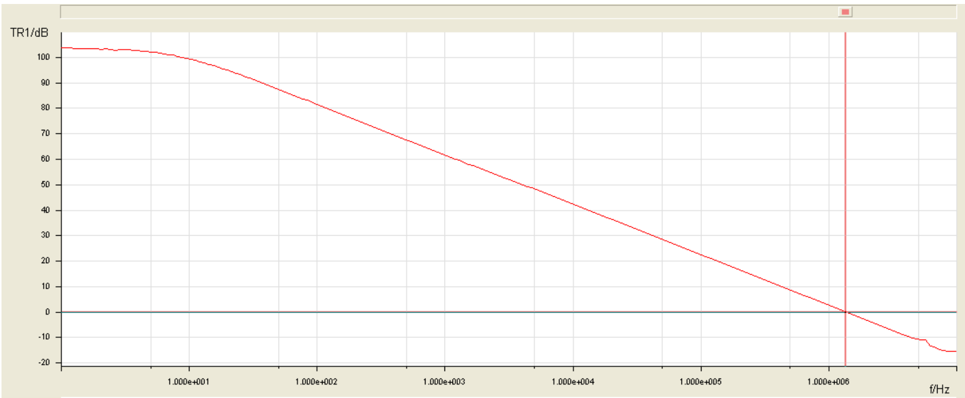


Note: Before you start the measurement **wait** a few minutes! The transient response of the feedback network in combination with the Op-Amp is quiet long. So make sure that the output voltage of the operational amplifier is approximately zero (with an oscilloscope) before you start the measurement and you will receive the open loop gain & phase.



	Frequency	Trace 1		Trace 2	
Cursor 1	7,978 Hz		100,468 dB		-44,913 °
Cursor 2	3,484343 MHz		-7,990 dB		-135,301 °
delta C2-C1	3,484335 MHz		-108,459 dB		-90,388 °

With the 2 cursors you can evaluate the pole frequencies (phase shift of -45° and -135°). Also the transit frequency can be measured with the cursor (A=0dB)



	Frequency	Trace 1		Trace 2	
Cursor 1	1,357703 MHz		-0,019 dB		-106,996 °
Cursor 2					
delta C2-C1					

We compare them to the data sheet of TL081.

Conditions	**Measurement value**	**Data sheet value**
DC-Amplification	103.4dB	~106dB
1st Pole	7.97Hz	25Hz
2nd Pole	3.84MHz	7MHz
Transit Frequency	1.35MHz	3MHz

Answer to question 1 and 2: **How can I measure the open loop gain & phase?**

Does the open loop gain & phase correspond with the theoretical values described in the datasheet?

In this application note we demonstrated two possibilities to measure the open loop gain & phase. The second method is more useful because the measurement result is more interesting. As we see from the table above, the theoretical values and the measurement values differ a little bit but the approximate value can be evaluated.

Answer to question 3: **Where are the poles of the examined operational amplifier?**

The poles of an Op-Amp are interesting for the stability criteria. They can be identified by an additional phase shift of -45° and an amplitude attenuation of -3dB. With cursors the frequency of the pole can be evaluated because the Op-Amp is a phase minimum system.

Answer to question 4: **What is the DC-Amplification of the examined Op-Amp?**

The DC-Amplification is quiet the same as the Amplification at low frequencies. So we pick the amplification at 1Hz and compare it to the theoretical value. As we see in the table above, it only differs about 3dB.

4 Conclusion

In this application note it has been shown how Bode 100 can be used to measure op-amp parameters such as open loop gain & phase and cut off frequencies. Further on it was demonstrated how Bode 100 can measure the two dominating poles of an Op-Amp.

We would like to express our thanks to Prof. Dr. Martin Schubert for his great support during the development of this application note.

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