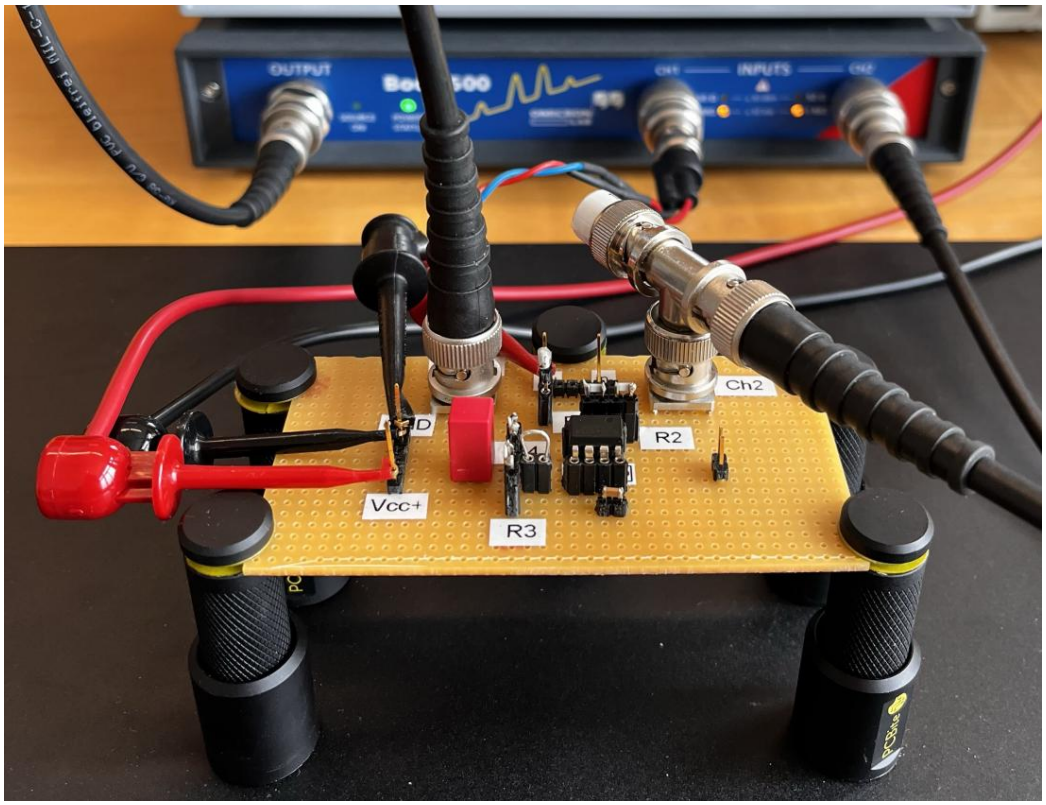
Bode 500 - Application Note

Closed-Loop Gain Measurement of a Single-Supply Operational Amplifier



By Luis Farfan
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Note: Basic procedures such as setting up, adjusting and calibrating the Bode 500 are described in the Bode 100, Bode 500 user manual available at: https://www.omicron-lab.com/downloads/vector-network-analysis/bode-100/

Note: All measurements in this application note have been performed using the Bode Analyzer Suite V3.52 Use this version or a newer version to perform the measurements shown in this document. You can download the latest version at https://www.omicron-lab.com/downloads/vector-network-analysis/bode-100/

1 Introduction

This application note describes how to characterize the closed-loop transfer function of a single-supply op amp in a non-inverting topology, using multiple gain configurations and how to measure the corresponding bandwidth of the amplifier circuit. Although datasheets typically provide gain-and-bandwidth plots for specific test conditions, practical design often requires direct measurement to verify real-world behavior.

2 Circuit Specification and Device Under Test

2.1 Single-Supply Op Amp

The single-supply non-inverting op amp configuration is shown in Figure 1. In this topology, the negative supply rail is connected to the system reference node (ground), while the positive supply rail is connected to the positive supply voltage, +Vcc. As a result, the op amp's operating voltage range is limited to positive voltages with respect to ground, restricting its ability to process signals that extend below the reference potential.

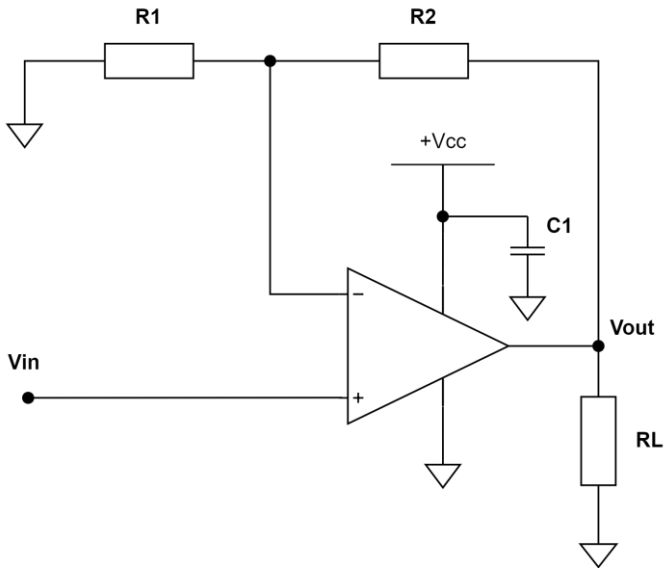


Figure 1: Schematic of the non-inverting, single-supply (+Vcc) op amp.

The nominal closed-loop amplifier gain in this configuration is the transfer function of the output voltage with respect to the input voltage of the circuit when feedback is applied. The feedback is defined by the resistors R1 and R2 using the equation (1). RL is the load resistor and C1 is a supply filter capacitor.

$$G = \frac{Vout}{Vin} = \left(\frac{R1 + R2}{R1}\right) \quad (1)$$

2.2 Device Under Test

The device selected for this application is the **Texas Instruments TL082CP** [1] FET-Input Operational Amplifier. Figure 2 shows the closed-loop gain frequency

response characteristic of the TL082CP datasheet [1]. For the single-supply configuration used in this example, the relevant datasheet parameters are:

- Supply voltage (Vs) is +30 V (maximum 42 V) where the +Vcc = 30 V and -Vcc = 0 V (ground).
- Minimum common-mode voltage range (VCM) 3 V, and maximum 30 V.
- Minimum peak output voltage swing (with RL = 10 kΩ) 1.5 V and the maximum 28.5 V.
- Gain-bandwidth product of 5.25 MHz.

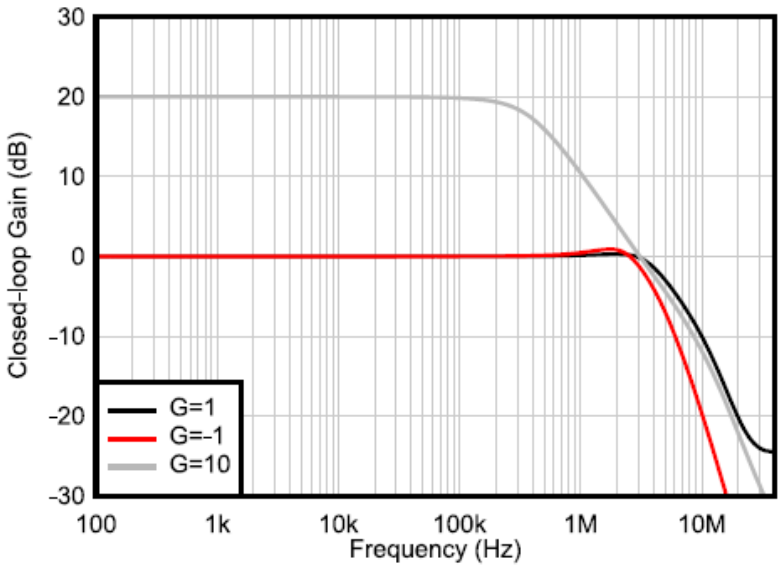


Figure 2: Closed-loop gain vs. frequency (Vs = ±20 V, VCM = Vs/2, RL = 10 kΩ, CL = 20 pF).

3 Closed-Loop Gain Measurement Setup and Results

3.1 Op Amp Input and Output Limitations

Under single-supply operation, the linear operating range of the amplifier is primarily constrained by two parameters: the input common-mode voltage range (VCM), and the maximum peak output voltage swing (VOM).

The voltage at the op amp inputs must remain within the specified VCM range. If the input common-mode voltage exceeds these limits, the amplifier may leave its linear operating region, resulting in an inaccurate or distorted output.

Similarly, the output voltage must remain within the specified VOM limits. If the required output voltage approaches either supply rail, the output stage may saturate or clip.

3.2 DC-bias Requirements

The sinusoidal output signal generated by the Bode 100 or Bode 500 is centered at 0 V and therefore includes negative voltage excursions. In a single-supply op amp circuit, applying this signal directly to the non-inverting input, Vin, may drive the input voltage outside the valid VCM range. To maintain linear operation, a DC-bias voltage must be added to the AC test signal.

3.3 Auxiliary Network and Signal Levels

The required DC-bias voltage can be generated using an auxiliary resistive voltage divider (R3 and R4) connected between +Vcc and ground. An AC-coupling capacitor C2 is then used to superimpose the Bode 100 or Bode 500 output signal onto this DC operating point while preventing the bias voltage from being applied to the instrument's OUTPUT port, as showed in Figure 3.

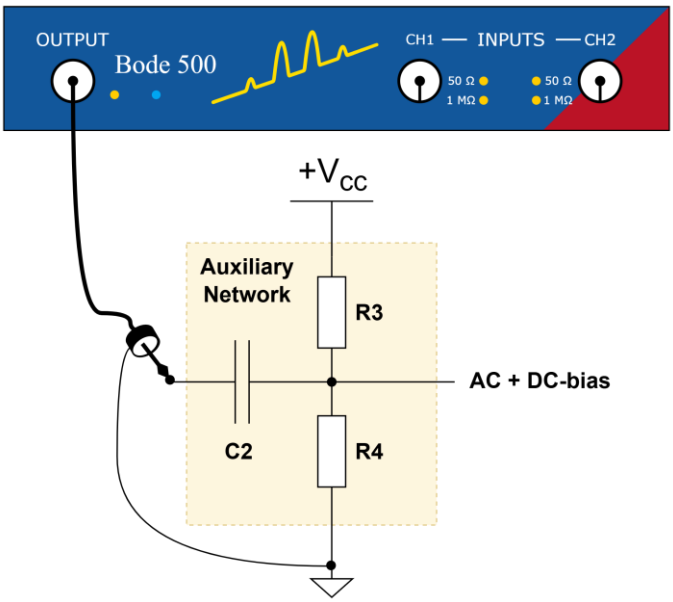


Figure 3: Voltage divider as auxiliary network to DC-bias the sine wave signal.

The coupling capacitor C2 (3.3 µF) together with the voltage divider resistors R3 and R4 forms an R-C high-pass filter, as shown in Figure 4. To minimize the influence of this filter on the measured signal amplitude, the corner frequency[1] (f_c) is set to be significantly lower than the lowest frequency of interest. The expression used to calculate the corner frequency is given in equation (2).

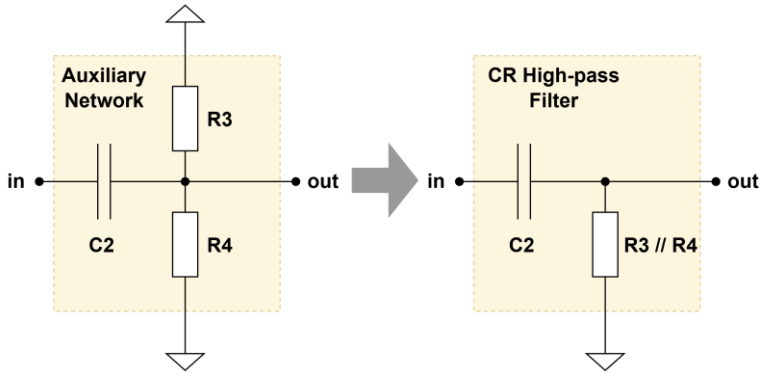


Figure 4: Auxiliary network behaves as a C-R high-pass filter.

[1] The high-pass filter corner frequency was designed to be lower than 20 Hz.

$$f_c = \frac{1}{2\,\pi\,C2\,R3//R4} \tag{2}$$

Figure 5 illustrates the corresponding signals levels for an example measurement using the Bode 500. In this example, the op amp is powered from +Vcc = 30 V, configured for a closed-loop gain of 4, and loaded with RL = 10 kΩ[2].

The yellow waveform represents the Bode 500 OUTPUT port signal, centered at 0 V. The auxiliary network shifts this AC signal to a DC level[3] of 3.75 V before it is applied to the op amp non-inverting input. With a close-loop gain of 4, the corresponding output DC level is 15 V, and the AC signal is amplified by the same factor (green waveform).

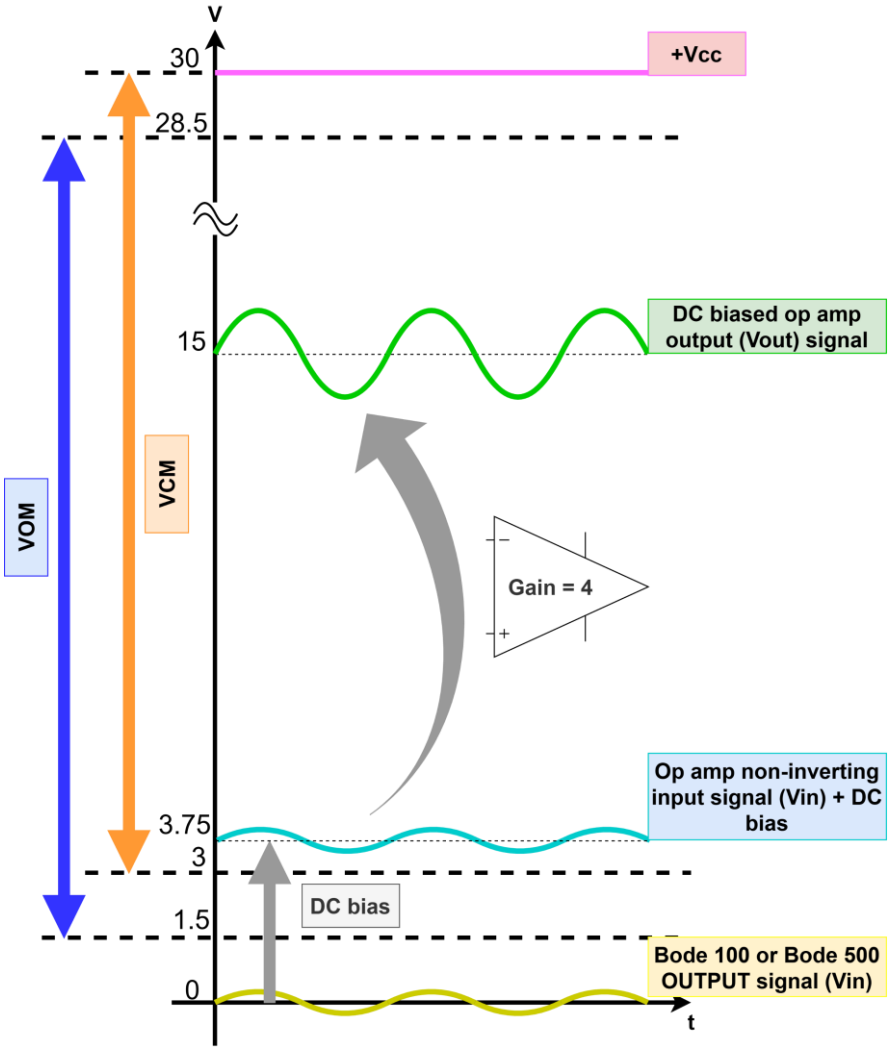


Figure 5: Op amp input and output signals with a gain of 4.

[2] Op amp datasheet condition.

[3] 3.75 VDC is chosen to maintain the output voltage at the center of the whole range.

The orange double-headed arrow in Figure 5 indicates the valid VCM range, while the blue double-headed arrow indicates the available VOM range. These limits are shown for illustration and must be determined from the op amp datasheet for the actual supply voltage, load, and operating conditions.

As the closed-loop gain increases, a given input amplitude produces a larger output amplitude and therefore reduces the remaining margin to the output swing limits. The DC-bias voltage and the Bode 500 output amplitude must therefore be selected together to ensure that both the input and output signals remain within their respective linear operating ranges.

3.4 Circuit Schematic and Setup

Figure 6 shows the complete circuit schematic and the connections to the Bode 500, and **Error! Reference source not found.** the physical setup and corresponding circuit under test.

The Bode 500 OUTPUT port is connected to the Vin node through the AC-coupling capacitor C2 using a 0.5 m BNC coaxial cable. This capacitor blocks the DC-bias voltage while coupling the AC excitation signal into the op amp's non-inverting input.

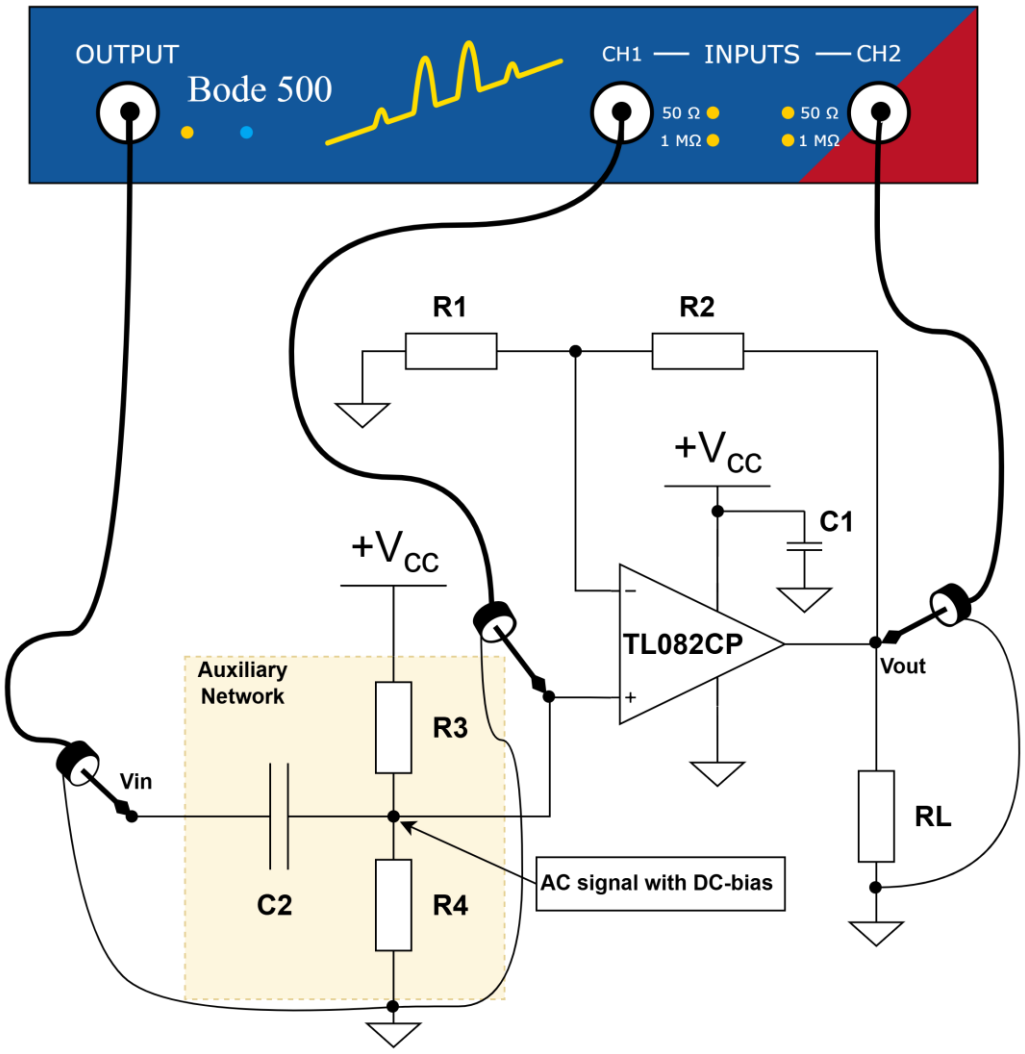


Figure 6: DUT, the Bode 500 and the circuit setup schematic.

The voltage divider formed by R3 and R4 establishes the DC operating point at the non-inverting input. The feedback network sets the closed-loop gain of the amplifier, and the load resistor, 10 kΩ soldered in a BNC connector, is connected from Vout to ground.

Channel 1 (0.5 m coaxial cable + pigtail connectors) measures the DC-biased input signal at Vin, while channel 2 (0.5 m BNC coaxial cable) measures the amplifier output Vout. The Bode 500 determines the closed-loop transfer function from the rate of these two measured signals: CH2/CH1. The physical implementation of the circuit and its connections to the Bode 500 are shown in **Error! Reference source not found.** below.

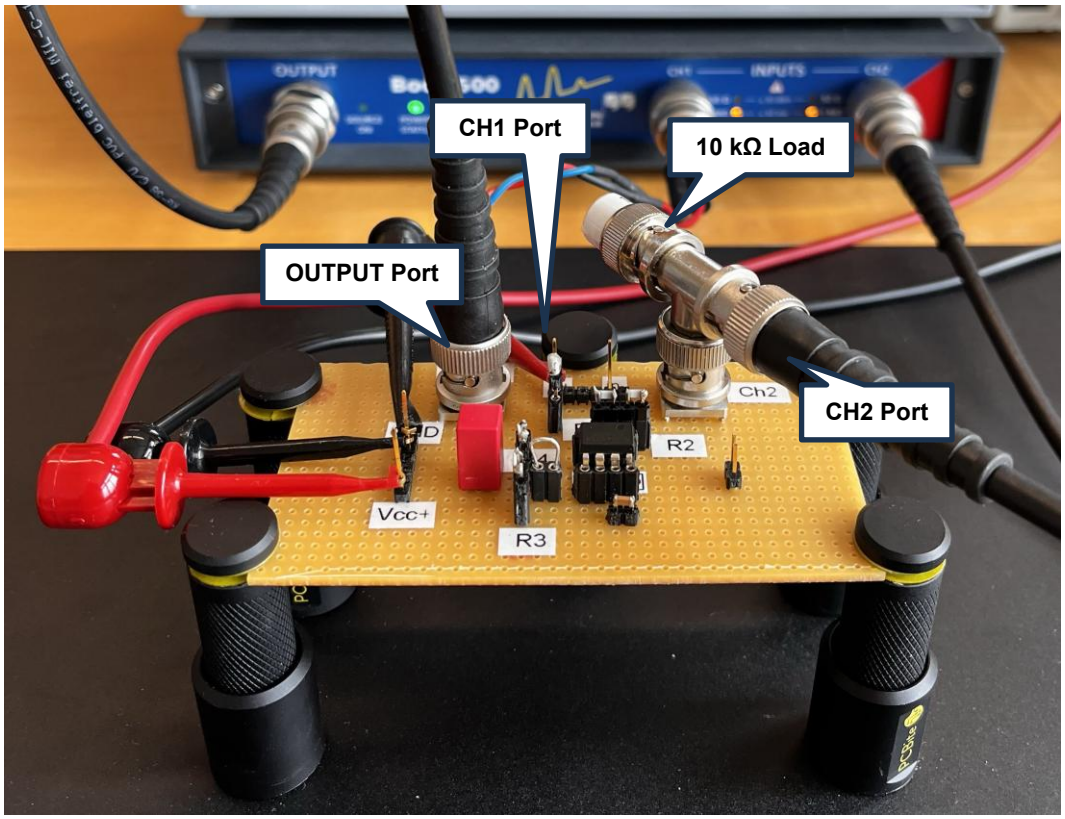


Figure 7: Circuit under test and Bode 500 ports connections.

Capacitive Load Impact

Load capacitances at the op amp output, including capacitances from cables, PCB traces, probes, or the following stage, can affect the measured closed-loop response. The finite output impedance of the op amp and the load capacitance form an additional pole in the amplifier response, which can introduce extra roll-off and phase lag. In a closed-loop gain measurement, this may appear as reduced bandwidth, gain peaking, or additional phase shift, which indicates that the capacitive load is degrading the amplifier's stability margin.

In this document, the DUT was connected to the Bode 500 using coaxial cables. This configuration results in significant capacitive loading as the cable capacitance is added to the input capacitance of the Bode analyzer.

3.5 Measurement Setup

To measure the closed-loop gain, the Gain / Phase measurement type is selected in the Bode Analyzer Suite (BAS). In this configuration, the transfer function response is obtained as the voltage ratio (gain) between the output and the biased input, assigned to CH1 and CH2, respectively.

The BAS settings, such as the frequency range, source level, and receiver bandwidth, are shown in Figure 8.

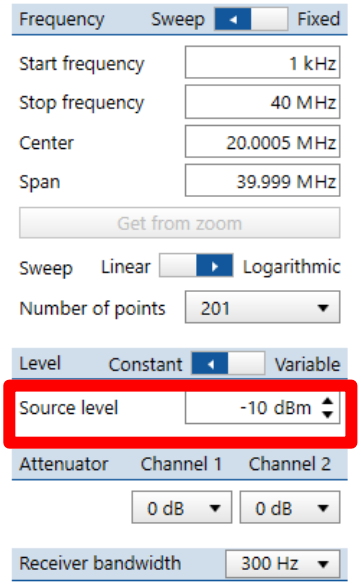


Figure 8: BAS settings

Source Level

The selected source level for most of the measurements is -10 dBm as shown in Figure 8. This level was chosen to ensure the input signal as well as the output signal remains within the lower and upper limits of the VCM and VOM (see Figure 5).

Relationship between dBm and RMS Voltage

The output signal of the Bode 100 and Bode 500 is referred to the source level in dBm, a logarithmic unit that expresses power relative to milliwatts, such that 0 dBm = 1 mW at a 50 Ω load.

As illustrated in Figure 9, the output signal of the Bode 100 or Bode 500 includes an internal 50 Ω source impedance. The configured source level is referenced to a 50 Ω termination load as shown in Figure 9a. Under this condition, the power corresponding to the selected dBm value is delivered to and dissipated in the load.

The output power P in Watts can be calculated from the configured source level in dBm using:

$$P = \frac{10^{dBm/10}}{1000} \tag{3}$$

The corresponding RMS voltage at a 50 Ω load is then given by:

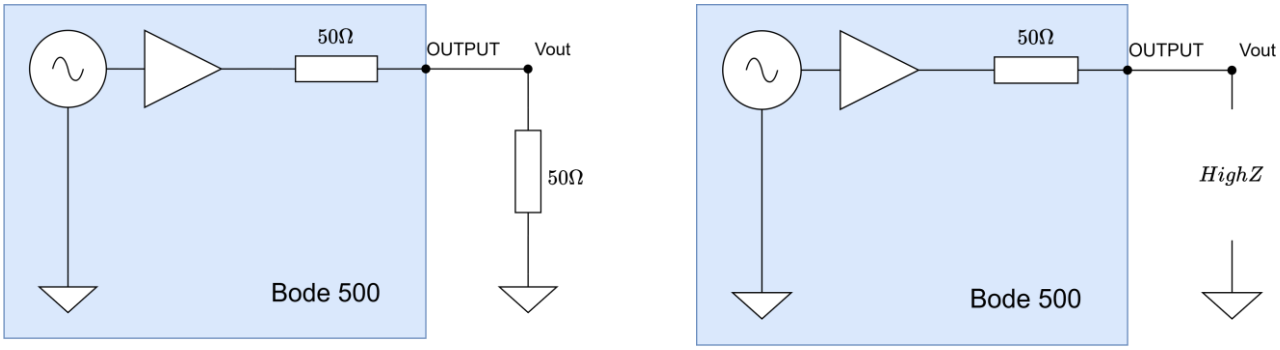
$$V_{RMS} = \sqrt{P \cdot 50\Omega} \tag{4}$$

The calculated value represents the nominal output voltage for a 50 Ω terminated load.

When the OUTPUT port is connected to a high-impedance load ($HighZ$), as shown in Figure 9b, virtually no current flows through the internal 50 Ω source resistance. As a result, the output voltage Vout measured at the connector is approximately twice the nominal voltage calculated for a 50 Ω load.

In the measurement setup, the Bode 500 OUTPUT port is connected to a high-impedance input network. Therefore, the actual AC excitation voltage applied to the circuit under test is approximately $2 \cdot V_{RMS}$, where the V_{RMS} is calculated using equation (4).

If the OUTPUT port is shorted, zero voltage will appear at the Vout node.



a) 50 Ω load impedance

b) High impedance load

Figure 9: Bode 500 output signal through the OUTPUT port at specific load termination.

3.6 Measurement Result

Figure 10 shows the measured closed-loop frequency response of the single-supply non-inverting operational amplifier for several gain configurations. Each curve corresponds to a specific feedback network and auxiliary bias network. The component values are listed in Table 1.

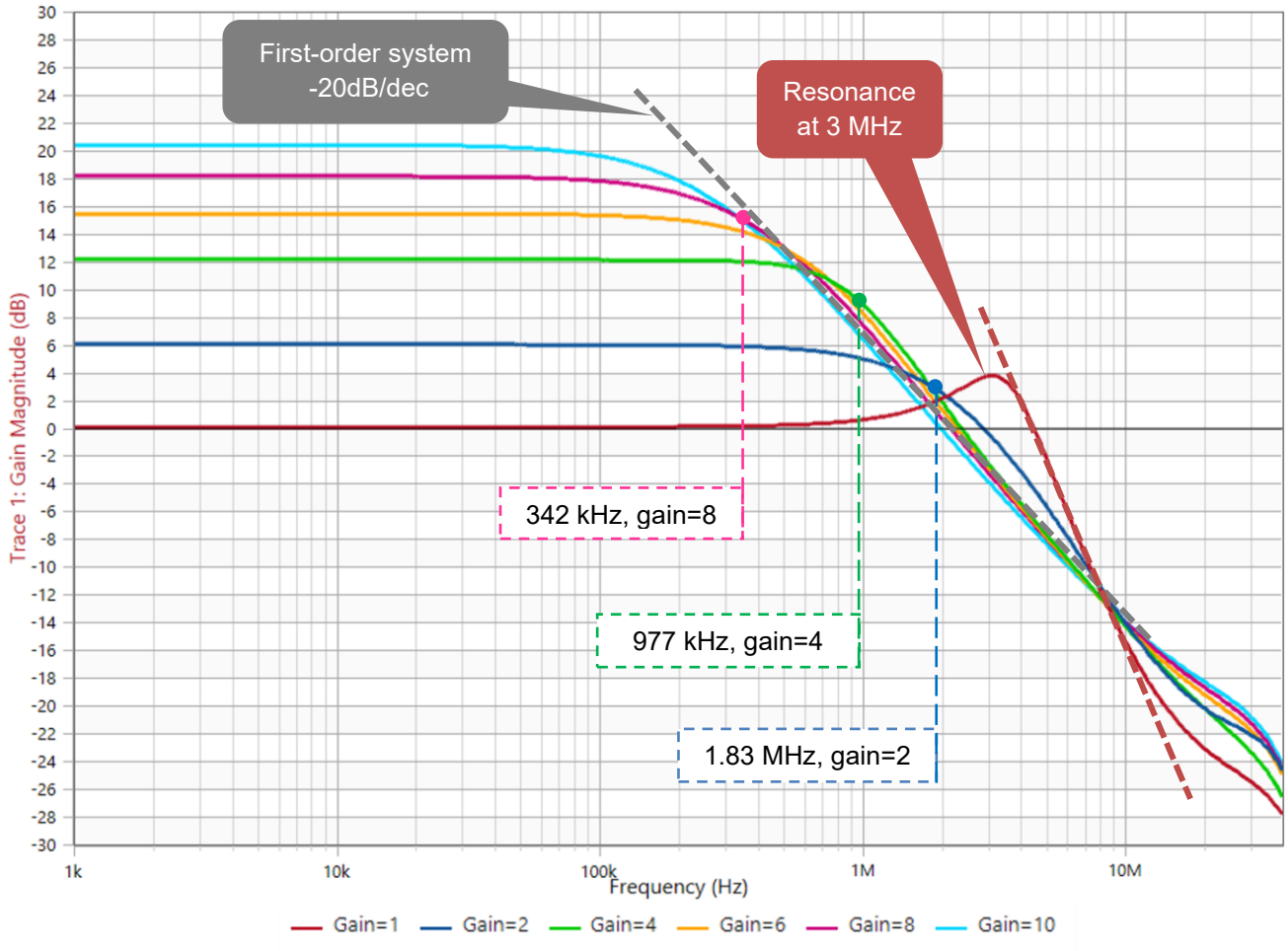


Figure 10: Non-inverting single-supply op amp transfer function response at different nominal gains and bandwidths of gain 2, 4 and 8.

The closed-loop gain of the operational amplifier and the capacitive load connected to its output influence the measured bandwidth[4]. As the gain of the closed-loop increases, the bandwidth decreases. For gains of 2 and higher, the measured responses exhibit approximately first-order behavior with a roll-off close to -20 dB/dec. Increasing the gain shifts the frequency response upward while moving the cutoff frequency to lower values.

At unity gain, however, the response differs significantly from the first-order behavior. A gain peaking of approximately 4 dB is observed near 3 MHz, indicating the presence of additional poles and reduced phase margin. Beyond the resonant peak, the response rolls off at approximately -40 dB/dec, which is characteristic of a higher-order system response. As the closed-loop gain increases, the peak diminishes and the response approaches a well-damped single-pole characteristic.

Bode 500 Output Signal [dBm]	Op Amp Gain	R1 [kΩ]	R2 [kΩ]	R3 [kΩ]	R4 [kΩ]	Cutoff Frequency
-10	1	100	1	10	10	5.24 MHz
-10	2	1	1	10	3.3	1.83 MHz
-10	4	10	30.3	33	4.7	977 kHz
-10	6	10	48.9	67.7	10	560 kHz
-10	8	10	70	90	10	342 kHz
-12 (+VCC=33V)	10	10	90	100	10	222 kHz

Table 1: Bode 500 output signal, op amp gain, resistors values, and cutoff frequency.

The capacitive load at the op amp output is an important factor influencing the frequency response. In the measurement setup, the 0.5 m coaxial cable contributes approximately 50 pF of capacitance, in addition to the 25 pF input capacitance of the Bode 500 and parasitic capacitances from the PCB.

The measured bandwidth values are valid for the specific setup used in this application note. Since the datasheet specifies the test conditions under a load capacitance of 20 pF, the results may differ from those obtained in this measurement setup.

[4] Is the -3dB cutoff frequency relative to the DC gain.

4 Conclusion

This application note presents a simple, practical, and straightforward approach for measuring the closed-loop gain response of a single-supply operational amplifier using the Bode 100 or Bode 500.

Appropriate circuit configuration and input biasing enable frequency response measurements in a single-supplied configuration.

The capacitance of the measurement connections can significantly influence the frequency response of the circuit under test. External active or passive probes can be used to reduce capacitive loading and evaluate the circuit under lower-load-capacitance conditions.

5 References

[1] Texas Instrument, *Datasheet TL08xx*, Sep. 2025. [Online]. Available: https://www.ti.com/lit/ds/symlink/tl084.pdf

[2] OMICRON-Lab, *Bode 100, Bode 500 Vector Network Analyzer. User Manual.* [Online]. Available: https://www.omicron-lab.com/fileadmin/assets/Bode-Analyzer-Suite/Documents/Bode-Analyzer-User-Manual.pdf



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