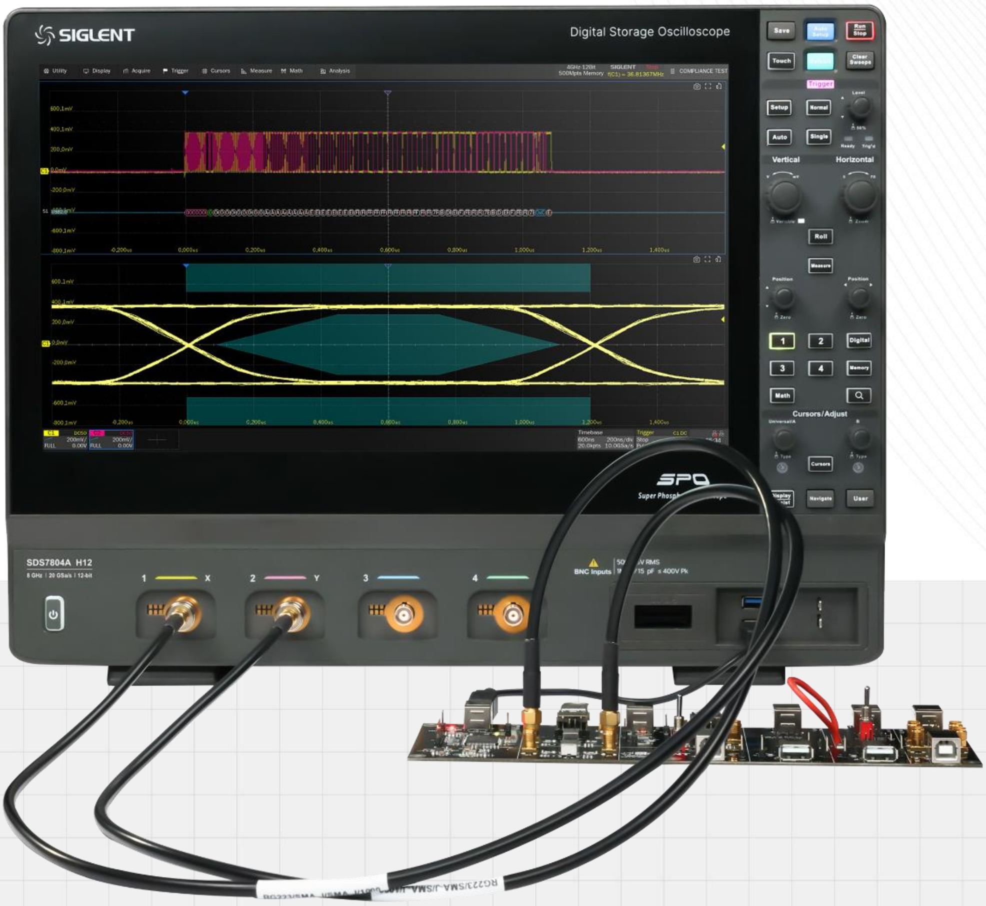
Bode Plot Solution

PSO2406-0006EN01



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Contact Us

SIGLENT Technologies Co., Ltd.

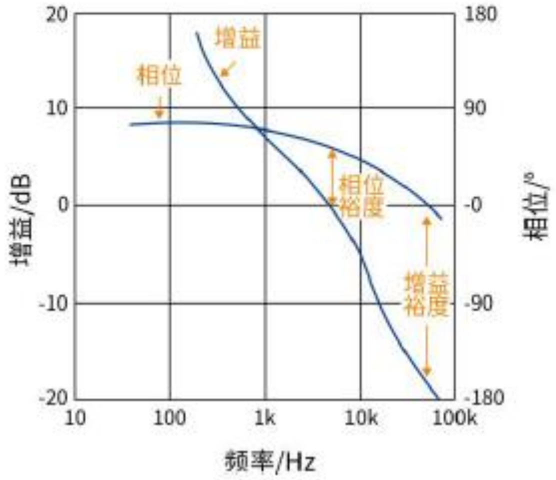
Address: Building 1, 4 & 5, Antongda Industrial Park, Zone 68, Bao'an District, Shenzhen, Guangdong, China
Service Hotline: 400-878-0807
E-mail: support@siglent.com
Website: https://www.siglent.com

1 Introduction

The Bode plot was invented in 1930 by the Dutch-American scientist Hendrik Wade Bode. He developed a simple yet accurate method to plot gain and phase. Due to phonetic translation, it is sometimes also referred to as a Bode diagram or Bode chart.

Bode plots are typically used to analyze the frequency response of a system. In AC signal processing circuits, the signal frequency range can be very wide, from Hz to kHz, even MHz. Voltage gain can also range from a few times to millions. To represent such a wide range of variation within a single coordinate system, Bode plots are often used to compress the scale.

Bode plots are widely applied in power supply design, particularly for power supply loop stability analysis. This involves plotting the gain and phase of the output voltage as a function of the frequency of an injected test signal to create a Bode plot. The Bode plot is then used to analyze switching power supply circuit parameters and determine stability. A Bode plot consists of a gain curve and a phase curve. The horizontal axis is frequency in Hz. The vertical axis of the gain curve is the logarithmic magnitude in dB, and the vertical axis of the phase curve is phase in degrees. The key reference parameters are Gain Margin, Phase Margin, and Crossover Frequency.



Gain Margin refers to the difference in voltage gain when the phase is 0°. To stay away from the instability point, a gain margin greater than 12 dB is generally required.

Phase Margin refers to the phase difference when the voltage gain is 0 dB. In engineering practice, it is generally required that the loop phase margin be greater than 45° under room temperature, standard input voltage, and normal load conditions to ensure system stability under various errors and parameter variations. When load characteristics or input voltage vary significantly, the loop phase margin should be greater than 30°. It should be noted that a larger phase margin increases system stability but slows down the system response; therefore, it is generally required to be less than 80°.

Crossover Frequency (also called bandwidth) is the frequency at which the gain is 0 dB. It reflects the speed of the control loop response. Generally, a wider bandwidth indicates better suppression capability for load dynamic response, smaller overshoot/undershoot, faster recovery time, and greater system stability. It is typically set to around 5% to 20% of the switching frequency.

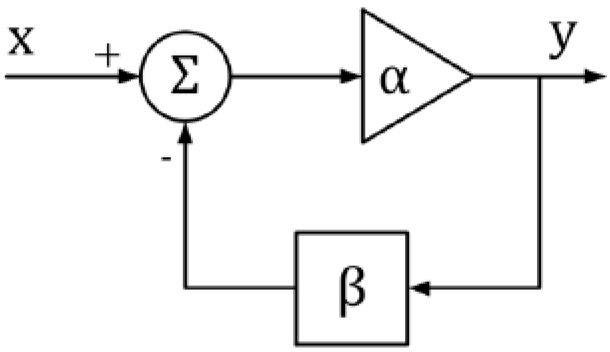
2 Challenges

While Bode plots allow for the quantification of a power supply's frequency response characteristics, enabling optimization towards greater stability without blind trial and error, some challenges exist: selecting the injection point for the disturbance signal, setting the frequency sweep range, and determining the amplitude of the injection signal, among others. Additionally, some engineers might opt for dedicated loop analyzers or frequency response analyzers, which have relatively limited application scenarios and can be expensive

3 Solution

3.1 Stability of Feedback Systems

A voltage regulator is essentially a feedback amplifier capable of delivering very high output current. Therefore, feedback amplifier theory is equally applicable to voltage regulators (hereafter referred to as power supplies). According to feedback theory, the stability of a feedback system can be determined from its system transfer function. In engineering practice, the Bode plot of the loop gain is typically used to judge system stability. Figure 2 shows a typical feedback system. The closed-loop transfer function A is the mathematical relationship between input X and output Y. The loop gain T is the gain obtained after the signal travels once around the loop.



$$A = \frac{y}{x} = \frac{\alpha}{1 + \alpha\beta}$$

$$T = \alpha\beta$$

In a real system, since the forward gain $\alpha\alpha$ and the feedback factor $\beta\beta$ are both complex numbers, the closed-loop transfer function A and the loop gain T are also complex, meaning they have both magnitude and phase angle. When the magnitude of the loop gain T is 1 and its phase angle is -180°, the denominator of the closed-loop transfer function becomes 0, making its result infinite. This implies a system can sustain an output without any input, behaving as an oscillator. This contradicts a stable system where bounded input produces bounded response, indicating the system is unstable at this point.

3.2 Breaking the Loop

Theoretically, the loop gain can be obtained simply by breaking the feedback loop. Figure 3 illustrates how to break the loop in a feedback system. For theoretical calculation, the loop can be broken anywhere. However, we typically choose to break the loop between the output and the feedback network. After breaking the loop, a test signal i is injected at the breakpoint. After traveling once around the loop, it reaches the output as signal y. The mathematical relationship between y and i is the desired loop gain T.

The loop can be broken at any point

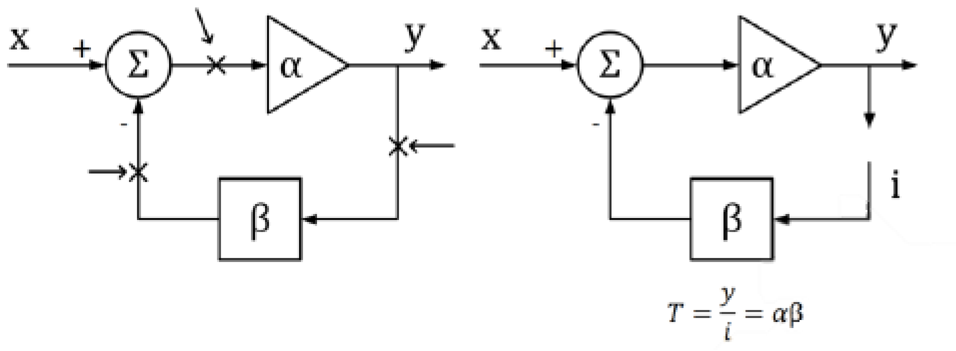


Figure 3: Breaking the Loop

3.3 Loop Injection

In reality, the feedback loop often serves to stabilize the circuit's DC operating point. Therefore, we cannot simply break the loop to measure loop gain. With the feedback loop open, the output may saturate due to factors like input offset, making any meaningful measurement impossible. To overcome this problem, measurement must be performed under closed-loop conditions. A feasible method is loop injection. Figure 4 shows a typical loop injection method. To minimize error, special requirements exist for the injection point selection: generally, the impedance looking into one side of the injection point should be much greater than the impedance looking into the other side. An ideal injection point is between the output and the feedback network. Other points, such as between the error amplifier and the power transistor, are also feasible.

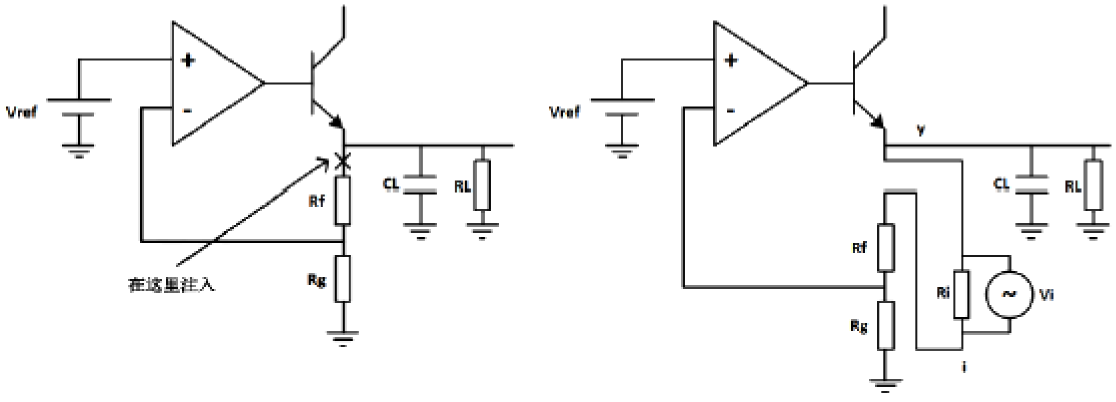


Figure 4: Loop Injection

To maintain the closed loop, a very small resistor is inserted at the injection point instead of breaking the loop. The injection signal is introduced into the loop through this injection resistor. The value of this injection resistor must be sufficiently small, typically much smaller than the equivalent impedance of the feedback network, ensuring its impact on the feedback loop is negligible. Picotest recommends using a 4.99Ω injection resistor when using a J2100A-type transformer or directly using the Siglent SAG1021I. Slightly larger resistors are also acceptable. On the other hand, because the injection resistor is in parallel with the injection transformer, a smaller injection resistor can lower the transformer's lower operating frequency limit, which is useful when measuring very low frequencies. In principle, signal injection should not affect the loop's DC operating point. To address the common ground issue between the signal source and the Device Under Test (DUT) in practical circuits, an injection transformer is often required, as shown in Figure 5, or a signal source with isolation can be used directly.

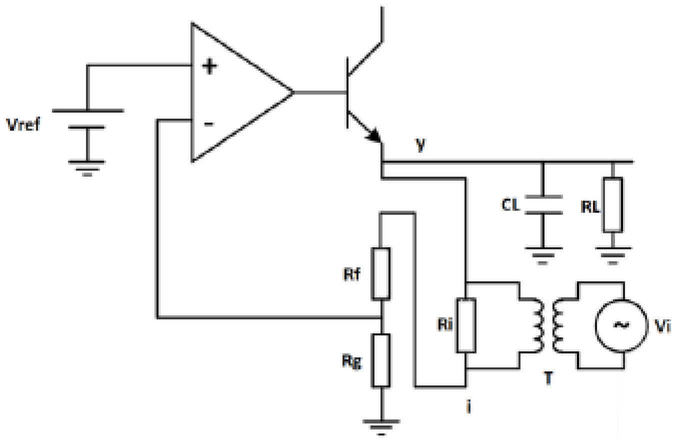
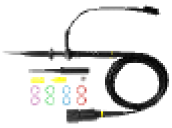


Figure 5: Loop Injection Using an Injection Transformer

The injection signal enters the loop from one end of the injection resistor, passes through the feedback network, error amplifier, and power transistor to reach the output, which is the other end of the injection resistor. Thus, the mathematical relationship between the output signal y and the injection signal i is the desired loop gain. It's important to note that we are measuring an open-loop parameter under closed-loop conditions. The measured phase will start at 180° and gradually decrease towards 0°. This differs from the theoretical loop gain obtained by directly breaking the loop, which would start at 0° and drop to -180°. Therefore, when calculating phase margin in this case, the reference should be 0°, not -180°.

3.4 Test Equipment

Image	Equipment	Description
	Oscilloscope	Standard with Bode Plot function, e.g., SDS800X HD, SDS2000X HD series, etc.
 	Isolated Signal Generator Signal Source	The Isolated Signal Generator is a hardware accessory for the oscilloscope. Paired with the oscilloscope, it can generate signals up to 25/50 MHz.
	Power Supply	E.g., SPD3000X, SPD4000X series, etc.
	Probe	1:1 passive probe (6MHz bandwidth), e.g., PP215
	Device Under Test (DUT)	Picotest VRTS v1.51. Recommended input voltage: 7-10V, input current < 100mA.

3.5 Test Setup Wiring

Picotest's VRTS v1.51 is a voltage regulator test board. The circuit on it is a linear power supply built with a TL431 and discrete transistors. It features a switch to select different output capacitors for varying loop responses. The schematic is shown in Figure 6.

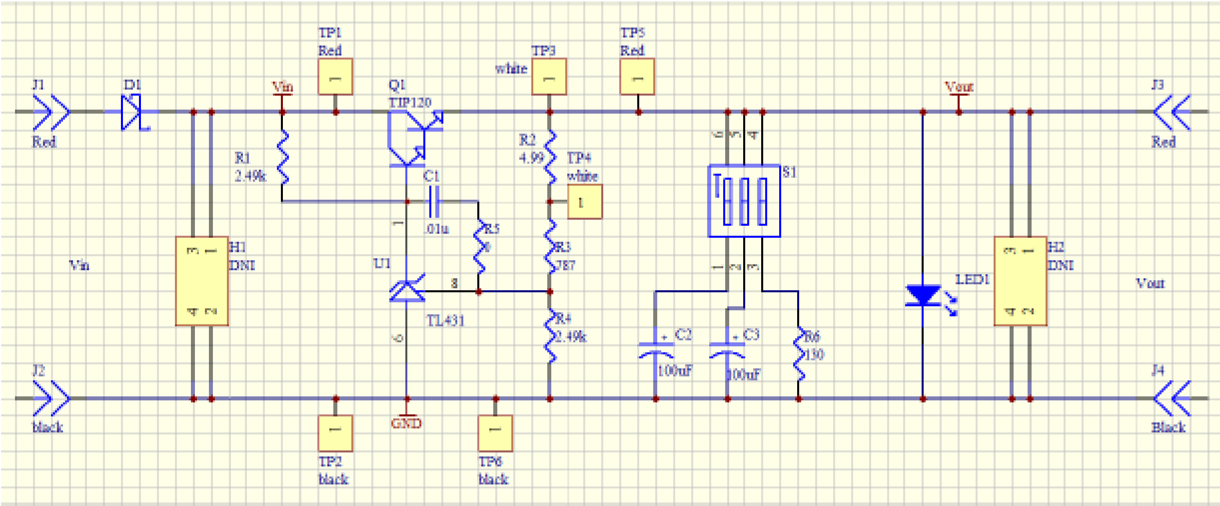


Figure 6: VRTS v1.51 Schematic

When testing the power supply loop response on the VRTS v1.51, TP3 and TP4 are the injection points. The wiring method is shown in Figures 7 and 8. The signal source SAG1021I connects to the oscilloscope via USB. Its output clips are connected in parallel with the injection resistor. This allows signal injection into the loop while preventing the DC operating point from being affected by ground loops between the signal source and the DUT. TP3 and TP4 are also connected to the oscilloscope. In the Bode Plot II software, TP3 is defined as DUT Output and TP4 as DUT Input.

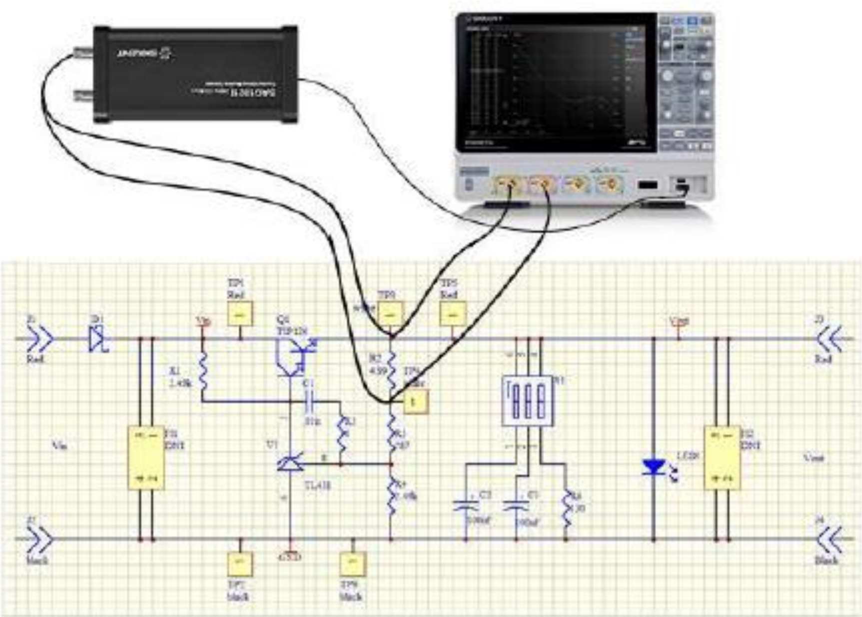


Figure 7: Wiring Diagram

Figure 8: Wiring Example

3.6 Instrument Settings

a)**Initial Setup:** After connection, begin configuration. First, set up the oscilloscope. Since the expected crossover frequency of the DUT is around 10 kHz, setting the measurement frequency range from 10 Hz to 100 kHz is sufficient. Before entering the Bode Plot software, it is recommended to set a 20 MHz bandwidth limit on the channels to be used.

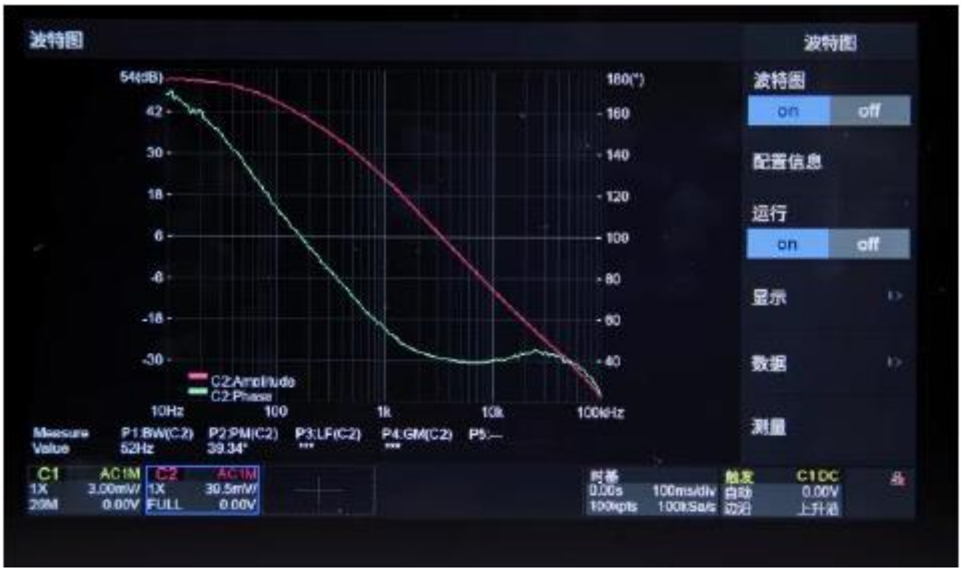
b)**Enter Bode Plot Mode:**Click "Analysis" to enter the Bode Plot interface. Click "Configuration." First is channel setup. As mentioned, set DUT Input to C1 and DUT Output to C2. Channel gain can be set to "Auto" or "Hold." When set to "Auto," the oscilloscope automatically adjusts the vertical scale based on signal amplitude. When set to "Hold," it maintains the scale prior to the run. Select "Auto." Choose the interface (e.g., USB). If using LAN, IP settings must be configured and saved. Then click "Connection Test" to verify successful connection between the oscilloscope and SAG1021I.

c)**Sweep Type:**There are two types: Constant Amplitude Sweep and Variable Amplitude Sweep. In Constant Amplitude Sweep, only start and stop frequencies need to be set; the amplitude remains constant within this range. Variable Amplitude Sweep means the stimulus amplitude can vary with frequency.

d)**Configure Profile:** At low frequencies, a larger stimulus amplitude can be set to improve measurement accuracy. Near the crossover frequency, the amplitude can be reduced to a certain level to minimize distortion, yielding better results. However, this requires an initial estimate of the approximate crossover frequency.

The software supports editing and saving up to 4 configuration profiles. Set the frequency mode to "Log." "Points" refers to the number of output frequency points per decade (e.g., between 100 Hz and 1 kHz). Set this to 40 for this example. More points provide higher sweep resolution. Set the amplitude unit to "V," and the load to "High Z." Then edit the profile. We'll create 5 nodes with frequencies set to 10 Hz, 100 Hz, 1 kHz, 10 kHz, and 100 kHz. We'll set the amplitude lower around 10 kHz, so amplitudes are set to 2 V, 2 V, 100 mV, 100 mV, and 1 V respectively. After setup, the polyline clearly shows the stimulus amplitude distribution. In actual testing, finding suitable configuration parameters often requires iterative adjustments by the test engineer.

e)**Finalize and Run:** After all settings are complete, set the power supply output to 8V and 0.05A, and enable the output. The LED on the DUT board should illuminate. Click "Run" to start the sweep. The final sweep result is shown in the figure below. The red curve represents magnitude, and the green curve represents phase.



f)**Data Analysis:** There are three methods for data analysis.
1. **Data Table:** Directly click "Data" to open the data list, which shows the magnitude and phase corresponding to each frequency point.
2.**Automatic Measurements:** Click "Measurements." Five measurement items are available: Upper Cutoff Frequency, Lower Cutoff Frequency, Bandwidth, Gain Margin, and Phase Margin.
3.**Cursors:** Use the knobs to slowly move the cursors. The display area continuously updates information such as phase and magnitude at the current frequency point.

Tip: If the gain or phase curve is not smooth, it could be due to excessive or insufficient injection voltage causing distortion in the C1/C2 waveforms, or the C1/C2 voltage being too small for the oscilloscope to detect properly. In such cases, exit the Bode Plot mode and observe the C1 and C2 waveforms at the abnormal frequency point to see if clear traces are visible on the screen. If the C1 and

C2 traces are not displayed well on the screen, adjust the output amplitude of the SAG1021I for different frequency bands according to your needs.

4 Summary

The Bode Plot solution provided by SIGLENT, when paired with the SAG1021I, can be used for measuring power supply control loop response, achieving ideal test results at an economical cost.

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