AC measurements on high-speed op amps

Introduction

Following the application note AN6365, the aim of this document is to review the specificities of high speed op amps for AC measurements, and provide practical solutions and tricks.

1 High-speed op amps

In this work, we will consider general purpose high-speed voltage feedback op-amps (VFA), with gain-bandwidth product in the range 10 to 100 MHz. These op-amps are widely used for phototodiode transconductance amplification, current sensing or as ADC drivers. Op amps in the GHz range used in RF designs are not considered, whereas some of the principles can be applicable.

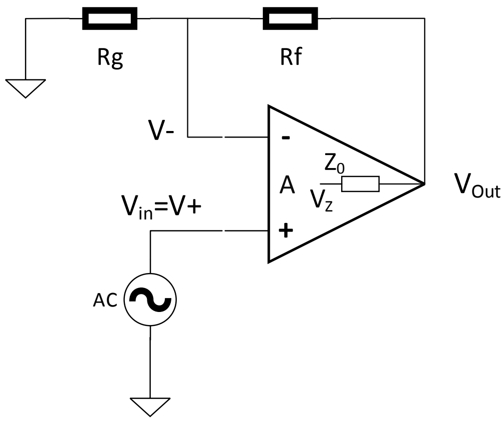
High speed op amps do not differ fundamentally from mid or low frequency op amps, but because of the maximum bandwidth value, the electrical length (propagation distance for one wavelength) will not be negligible compared to the measurement cables length. Thus, impedance adaptation is useful to avoid signal reflections and calibration is necessary to compensate for the phase shifts. High speed op-amps are also more sensitive to capacitive and inductive parasitics. Furthermore, the nominal capacitive load for the circuit – capacitive load for which the circuit is designed and qualified, and for which a good stability is guaranteed – is lower than for a low speed op amp.

Both the boards used for characterization and the measurement setup have to be optimized accordingly.

2 Circuit components choice

As demonstrated in AN6365, the value of the resistors in the op amp circuit must be chosen carefully and depend on the op amps characteristics.

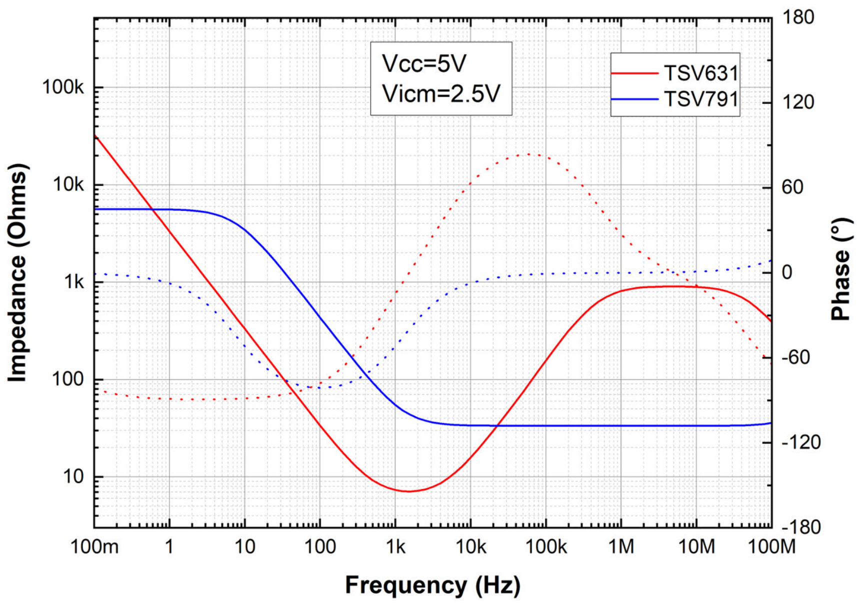
Figure 1. Schematic of the non-inverting op amp circuit with output impedance



For high speed op-amps, the resistors values should be lower that for lower frequencies op amps in order to minimize the impact of the input capacitance of the op amp, as demonstrated in AN6365 paragraph 3. Indeed, the combination of the feedback resistor and the parasitic capacitances at the op amp negative input (both intrinsic to the op amp, and parasitics on the board) will alter the feedback and ha e an impact on the stability of the system.

On the other hand, it is also essential to keep the feedback resistor value R_F large in comparison with the output impedance. However, this is easier to achieve on high speed op amps as the output impedance is generally lower. Figure 2 compares the open-loop output impedances of TSV631 (GBP = 900 kHz) and TSV791 (GBP = 50 MHz).

Figure 2. Open-loop output impedance of TSV791 and TSV631

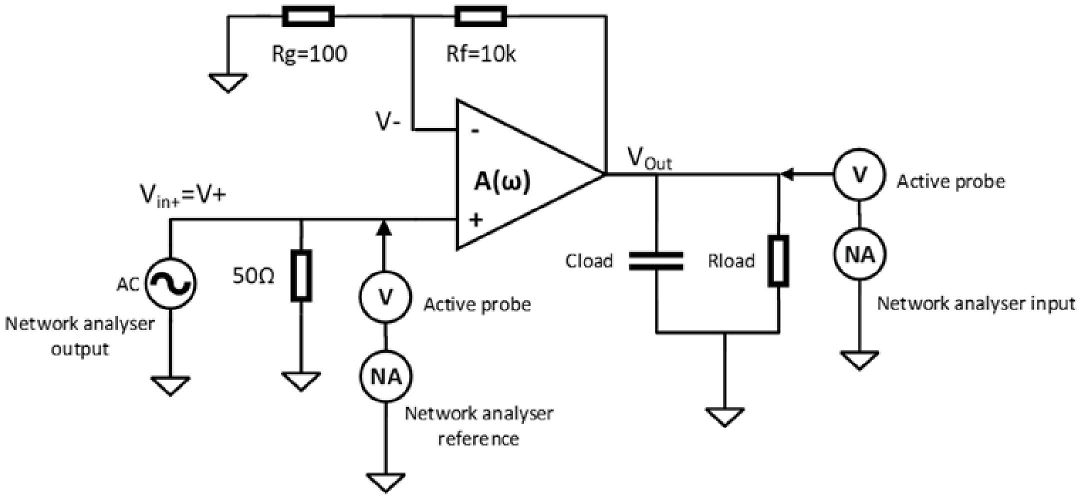


It is also important to note that many schematics of an op amp in non-inverting configuration use at the positive input a resistor of the same value as the gain resistor R_G. This is useful in some precision application to balance the input currents of the positive and negative inputs, when they are not negligible, particularly with bipolar input op amps which have higher input currents. However, for high speed applications and measurements, it should be avoided at it may create a direct RC when combined with the input capacitance of the op amp. Even if the cut-off frequency of this filter is above the GBP of the op amp, it can have an impact on the signal phase and introduce an error in the phase and gain margin measurements.

3 Impedance adaptation

Impedance adaptation at the op amp input is needed to avoid signal distortion when the electrical length is not negligible versus the cable length. It is pretty straightforward to achieve as an op amp has a very high input impedance in its bandwidth of use; this impedance can be considered as very large in front of 50 Ω, and good impedance matching can be achieved by placing a 50 Ω resistor as close as possible to the op amp input. However, the probe input impedance also has to be large versus 50 Ω, which is usually the case.

Figure 3. Input impedance adaptation on op amp measurement setup with probes

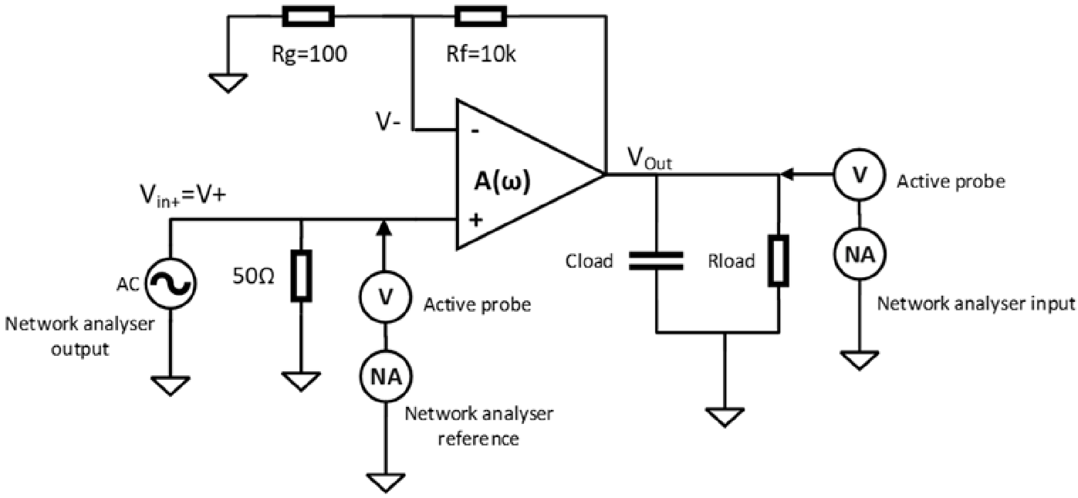


In this configuration, output impedance adaptation is usually not needed; as the high impedance output probe is placed as close as possible to the device, the signal path is short enough. Unfortunately, this configuration is difficult to use for temperature measurement, as the active probes cannot operate over the full temperature range of the op amp.

In order to perform temperature measurements in a thermal chamber without limitations on the length of the cables, it is necessary to adapt the impedances at the input and the output. To avoid the use of an active probe while measuring the input signal in the reference input of the network analyzer, a 50 Ω power splitter can be used (see Figure 2). In this case, the signal amplitude at the op amp input is reduced by a factor 2 in amplitude.

The adaption at the op amp output is less straightforward, as a usual op amp is not able to drive a 50 Ω impedance – or if it can, such an impedance is not the targeted measurement condition. The other issue is that, as stated in AN6365, the op amp characteristics are highly sensitive to the capacitance at its output; a long coaxial cable will be seen as a capacitive load. Placing a resistor with a value in the range of the nominal resistive load of the amplifier (typically, 10 kΩ or lower for high speed op amps) isolates the op-amp from the capacitance of the cable downstream, reducing the parasitic capacitance seen by the op amp. It also allows 50 Ω impedance adaptation from the resistor, when using a coaxial 50 Ω cable to link the board to the network analyzer input, which is 50 Ω.

Figure 4. **Input impedance adaptation on op amp measurement setup without probes**



It creates a voltage divider that strongly attenuates the signal – typically with a 10 kΩ resistor, the attenuation is 47.6 dB. However, this attenuation can be subtracted from the final measurement, or ideally taken into account at the calibration step. The main limitation to this technique is that the amplitude measured by the network analyzer will be much lower; in order to reach a good measurement repeatability, it may be necessary to increase the integration time, and increase the input signal amplitude.

4 Calibration

For AC measurement on high bandwidth op amps in the range 10 to 100 MHz, whereas we use a network analyzer, the measurement we try to perform is not a S-parameter measurement because we only measure the transmitted signal from the input to the output; we don't need to measure the signal reflection, neither the transmitted signal from the output to the input, which would be very low. In other words, we only measure the S_{21} part of the S parameter.

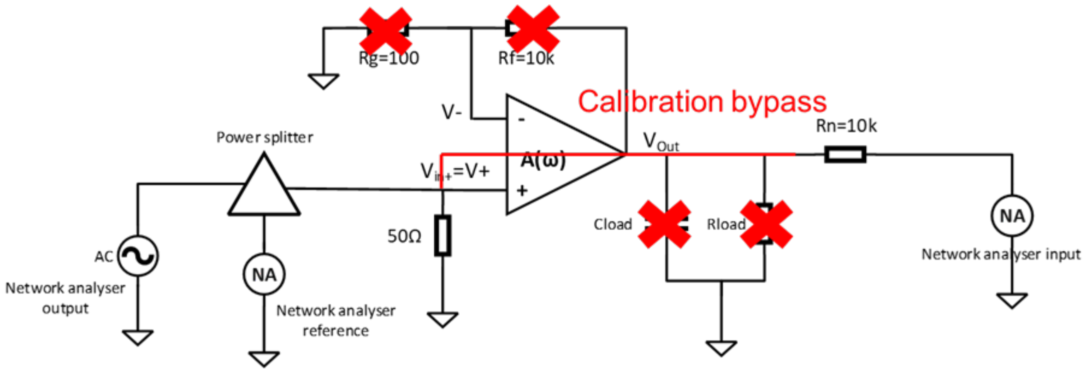
Also, the frequencies at play are too low to have significant loss and capacitive coupling between the coaxial and PCB traces to the DUT, if the system is properly setup. For these reasons, open and short calibrations usually performed for RF measurement are not useful.

However, a thru calibration may be useful if the electrical length is not negligible versus the signal path length, or more precisely the signal length difference between the reference and output signal. The thru calibration will compensate for the phase shift due to the signal path difference, that can directly affect the measured phase.

A thru calibration is also needed to compensate for the attenuation introduced by a series resistor as shown in Figure 2. Though simply adding the attenuation to the measured gain is possible, calibrating the system with the series resistor is simpler and more precise.

The calibration can be done by designing a calibration path identical to the measurement path on the measurement board, or more simply by soldering the In+ of the op amp footprint to the Out, an omitting the gain and load resistors, as proposed on Figure 3:

Figure 5. Calibration schematic



5 Input offset compensation

As demonstrated in AN6365, the schematic gain should be large enough in order to measure closed loop AC characteristics close to the theoretical (open-loop).

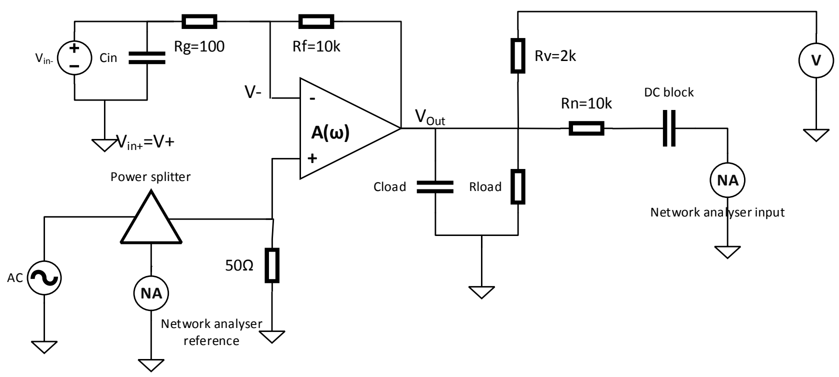
The DC output polarization is theoretically at ground level in all our previous measurement configurations, but this is not actually the case, as the op amp offset has to be taken into account. For example, for a non-inverting configuration (figure x), the output DC polarization will be:

$$V_{Out,DC} = -\left(1 + \frac{R_F}{R_G}\right).V_{io} \quad (1)$$

When V_{io} is large and V_{cc} is low, if the common mode voltage V_{icm} is set close to GND or V_{cc}, or when the input AC signal is set to a large value, the output stage of the op amp can saturate.

To avoid this, it is possible to use an external DC voltage source to shift the $V_{Out,DC}$ value. For example, in a non-inverting configuration:

Figure 6. Measurement schematic for offset compensation



In this case, the $V_{out,DC}$ can be expressed as:

$$V_{Out,DC} = \left(1 + \frac{R_F}{R_G}\right).V_{io} - \frac{R_F}{R_G}.V_{in-} \quad (2)$$

If the V_{io} is known, the V_{in-} can be set directly to compensate for the V_{io} value and get $V_{out,DC}$ = 0 V. However, it is easier to measure $V_{out,DC}$ and adjust the V_{in-} empirically.

This configuration is also useful in order to characterize the op amp AC characteristics variations with the input common mode (V_{icm}) and V_{out}, independently. Indeed, V_{icm} is set by shifting the op amp power voltages V_{cc+} and V_{cc-}, Vicm being always at GND. Then Vout can be set independently by setting the right V_{in-} value.

Practically, the schematic shown in figure 7 can be used.

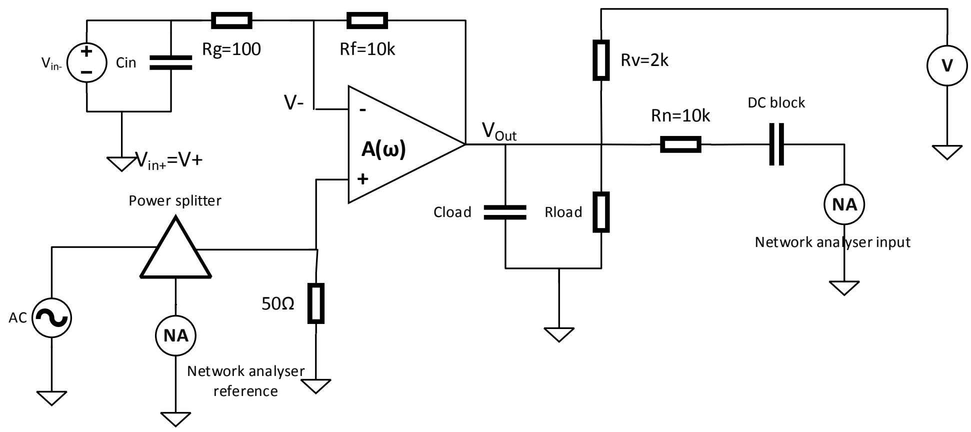


Figure 7. Practical measurement schematic for offset compensation

A large Cin capacitance is added in parallel with the DC voltage source, as the power supplies, DC sources and SMUs are not low impedance at the frequencies of the measurement. This capacitor is needed to lower the impedance at high frequency.

The voltmeter connected to the op amp output in order to measure the DC Vout bias is isolated by a large resistor Rv as close as possible to the op amp. Similarily to the Rn resistor, it avoids any impact of the capacitive parasitics of the trace and cable to the voltmeter.

Finally, a DC block (or large capacitor in series) is added to avoid any DC bias at the network analyzer input. This is useful when setting the V_{out} and V_{icm} at a different bias. Indeed, the voltage on the non-inverting input pin is always null and the V_{icm} is set by shifting the op amp power supplies. In this case, the V_{out} can be different from 0 V.

6 Signal amplitude adaptation

As explained in AN6365, the input signal should be low enough to ensure that:

- The output stage of the op-amp does not saturate, given the circuit gain and the characteristics of the output stage.
- The op amp is not in slew rate mode: $V_{In} < \frac{2.\pi.f}{SR.Gain}$.

When using a large output resistor for impedance adaptation as proposed in paragraph 3, the induced signal attenuation lowers dramatically the signal at the input of the network analyzer, and obtaining a good measurement repeatability may need to increase largely the integration time. In particular, the phase and gain margin are affected because the gain of the circuit is ≤1 and the signal amplitude is particularly low.

However, if the output saturation or slew rate limit are quickly reached at low frequency, at the phase and gain margin frequencies, the input amplitude can be increased. So, to improve the measurement precision and duration, the input amplitude should be set at different levels at low and high frequencies, or the measurement can be done in 2 steps : a first measurement in order to get the low frequency part of the Bode curve, and a second with increased amplitude (+20 dB or more) for the part of the curve around 0 dB and below.

7 Board design

PCB design for AC measurements on high speed op amps should be optimized to reduce the parasitics, both inductive and capacitive, that will have an impact of the measurements. In particular, high speed op amps being highly sensitive to the capacitive load, the parasitic capacitance on the output path should be reduced.

For signal integrity, it can be useful to used 50 Ω adapted lines. However, as such lines are more capacitive than a simple non adapted PCB trace, it is antagonist to the reduction of the parasitic capacitance. Consequently, only the lines before the 50 Ω input resistor, and after the output resistor Rn need to be adapted. For the other tracks, signal integrity will be guaranteed by using tracks as short as possible.

Figure 8. Practical measurement schematic with 50 Ω adapted lines

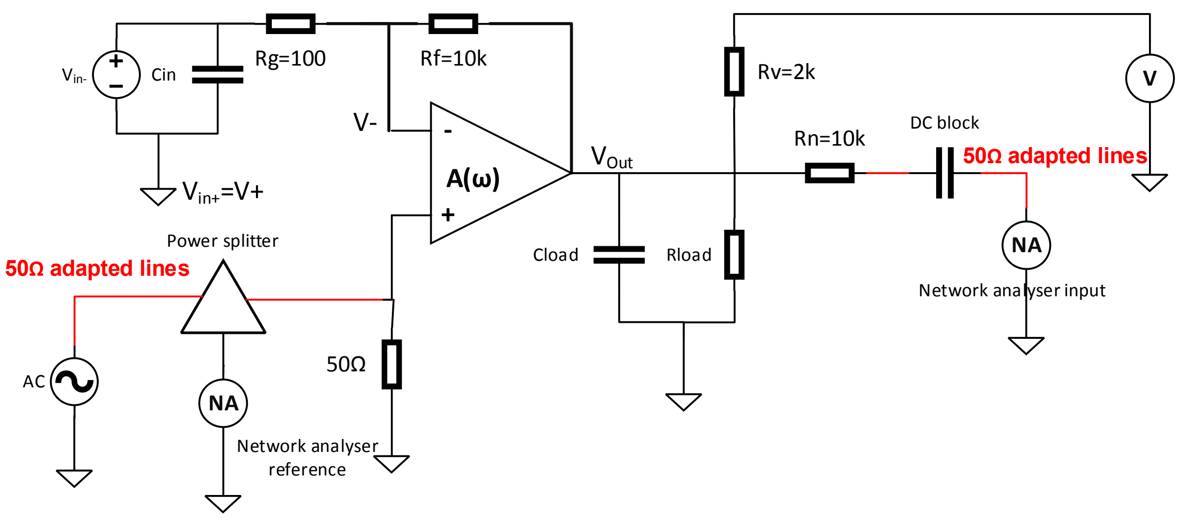


Figure 9 and Figure 10 show an example of measurement board allowing to use the different measurement techniques described in this document, as well as AN6365.

Figure 9. High speed AC measurement board schematic

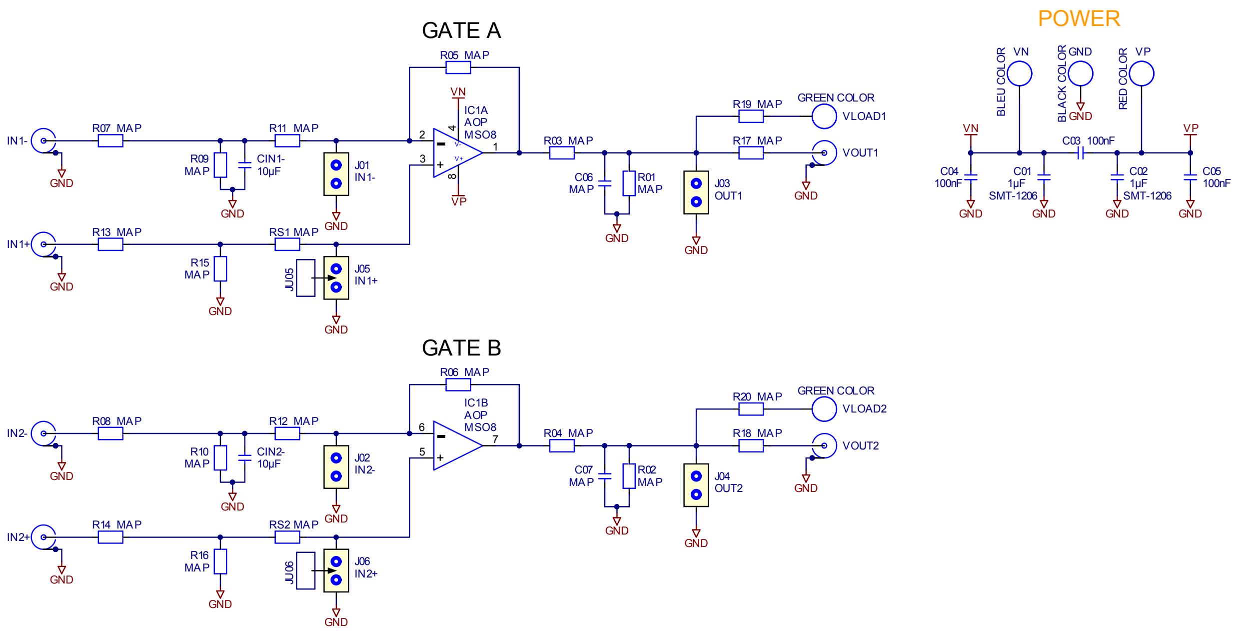
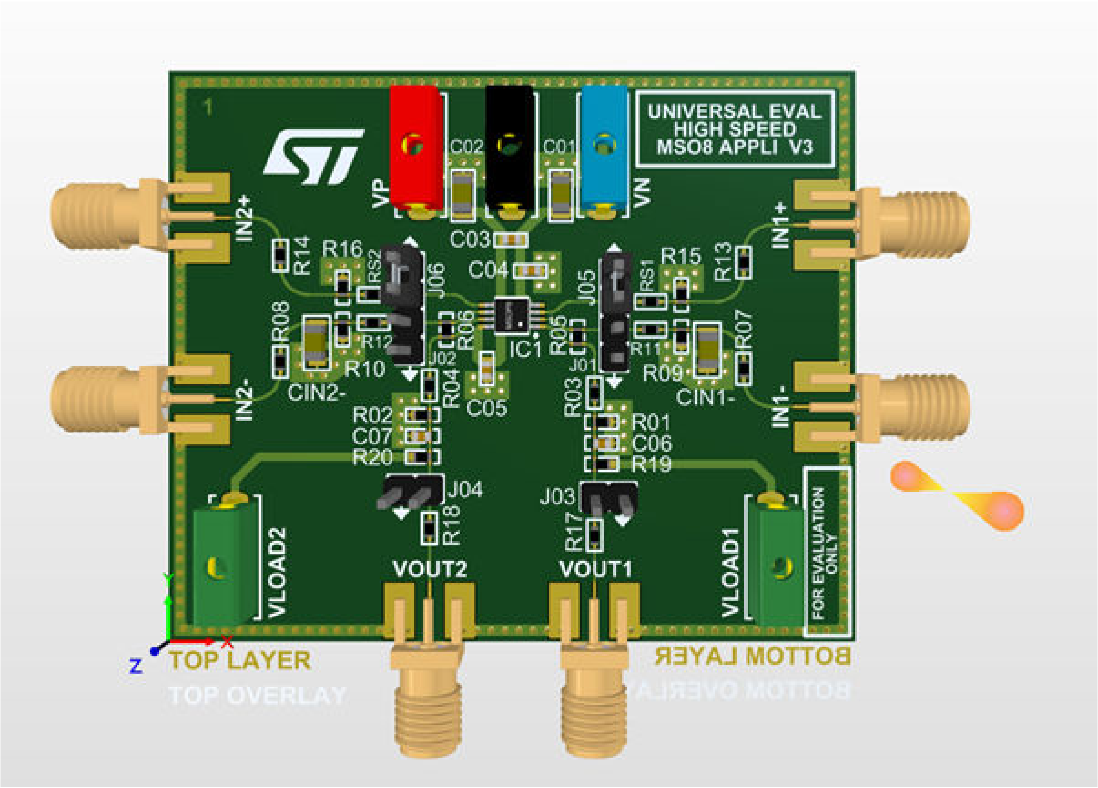


Figure 10. High speed AC measurement board 3D view



8 Conclusion

This application note presents methodologies, tricks and schematics to perform AC measurements on high speed op amps, typically with a GBP in the 10 to 100 MHz range.

The difficulty is usually that, in this frequency range, low frequency techniques have to be adapted, as the propagation time and signal reflection can be visible. However, usual RF techniques are not useful, either because the frequency is too low, or because impedance adaptation techniques are not usable. Practical measurement techniques and schematics are given.

Revision history

Table 1. Document revision history

Date	Version	Changes
20-Jan-2026	1	Initial release.

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