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Consider The Tradeoffs When Choosing Probes For 48-V Applications

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With growing power requirements necessitating voltage levels higher than 12 or 24 Vdc, markets for products powered by 48 Vdc are growing quickly. Consumer-related products and subsystems operating on 48 Vdc include cordless power and gardening tools, small propulsion motors, battery chargers, and dc-dc converters for computer servers. The technology also finds use in automotive applications. Mild-hybrid motors, electric-boost turbochargers, HVAC fans and compressors, adaptive lighting systems, antilock braking systems, stability systems, and fuel, water and oil pumps are all migrating to 48 V.

Simultaneously, GaN is displacing silicon in many applications because its faster rise times—about 1 ns—translate to better efficiency, smaller size and lighter weight. However, the faster rise times require about 1 GHz of oscilloscope and probe measurement bandwidth. A thorough understanding of the different types of probes available for use, and their tradeoffs, will allow you to make the best possible measurements of signals in your 48-V power-conversion systems.

This article looks at active and passive probe types that are candidates for measuring switching waveforms in 48-V power converters, particularly those using GaN power transistors. After identifying four probe classes, where they are used, and some example models, the discussion focuses on their use in low- and high-side gate drive measurements of GaN devices. The probe models cited in this article are all from Teledyne LeCroy, but in several cases there are comparable products available from other vendors.

The sources of various waveform characteristics such as overshoot, dips, ringing and noise are explored with explanations of how the different probe characteristics contribute to these effects. Side-by-side comparisons of the different probe measurements illustrate the impact of probe characteristics such as bandwidth, noise performance and CMRR on the measurements. The tradeoffs in using the different probe types are weighed with respect to the requirements of gate-drive measurements in 48-V systems. Along the way, some probing tips and guidelines are provided.

Oscilloscope Probe Options

A key to success in 48-V power-conversion measurements is choosing the right oscilloscope probe. You can find several classes of probes, ranging from low-voltage passive single-ended probes (which often come free with a new oscilloscope) to fiber-optic and active differential probe models. Four probe classes are worth investigating for probing 48-V designs.

Passive probes are commonly used in labs, mainly because they are supplied as standard equipment with new oscilloscopes. Low-voltage passive probes have 10x attenuation. High-voltage passive probes are similar to their low-voltage counterparts but offer higher attenuation (typically 100x vs. 10x), which will increase noise.

Examples of high-voltage passive probes include the Teledyne LeCroy PPE and HVP series. They offer bandwidths of 500 MHz and single-ended voltage ranges up to 6 kV. Attenuation is 100x and loading is 10 MΩ in parallel with 7.5 pF. These probes may be used if you can tie the probe reference to ground. They are limited to probing the low side of a gate-drive circuit, and some lab managers may not permit their use at all on power conversion circuits.

High-voltage active differential probes employ high-attenuation galvanic voltage isolation. Generally, they offer 100- to 200-MHz maximum bandwidths, sometimes as high as 400 MHz, and reasonable loading (such as 10 MΩ in parallel with 2.5 pF).

Teledyne LeCroy offers its HVD series active differential probes, which feature differential voltage ranges extending from 2 to 8 kV and common-mode ranges extending from 1 to 6 kV. Attenuation is 50x to 2,000x (depending on common-mode and differential voltage measurement range), and CMRR is 85 dB at 60 Hz and 65 dB at 1 MHz.

Due to their higher attenuation, high-voltage active differential probes in general will have more noise, but the HVD series offers exceptional noise performance for this class and may be suitable for GaN device measurements in cases where the rise times are approximately 5 to 10 ns or slower.

High-voltage active single-ended fiber-optic probes use optical instead of galvanic isolation. Teledyne LeCroy offers the HVFO108, which provides a 150-MHz bandwidth and 2- to 80-V voltage ranges. Common-mode voltage range is virtually unlimited. Attenuation is 1x to 40x depending on voltage range and CMRR is 140 dB.

A fourth alternative is a new class of probes: Teledyne LeCroy's DL-HCM series high-common-mode active differential 1-GHz probe (Fig. 1). It employs low-attenuation galvanic voltage isolation. Its differential and common-mode (dc plus peak ac) voltage ranges are 80 V, surpassing the 12- to 20-V common-mode voltage ranges of typical low-voltage differential probes and providing headroom for 48-V design testing.

Loading is 200 kΩ in parallel with 0.6 pF for an input impedance of 2.5 kΩ at 100 MHz. CMRR is exceptionally good—80 dB at 10 kHz, 55 dB at 1 MHz and 50 dB at 100 MHz. This probe offers excellent noise performance because attenuation is low. It is particularly suitable for power semiconductor gate-drive and switching-loss measurements, and system input/output measurements.

Fig 1. The DL-HCM series high-common-mode active differential 1-GHz probe.

Low-Side Vs. High-Side Measurements

Power conversion circuits typically contain two types of test points: the first, referenced to the board's ground plane; the second, referenced to a voltage greater than the board's ground (dc bus voltage). The latter is often referred to as a "floating" measurement.

Many times, power conversion systems will tolerate the board ground point connected to oscilloscope (earth) ground. In this case, low-voltage probes with common-mode ratings less than the dc bus voltage may be used to safely make measurements. However, this is not true for “floating” measurements. A low-side gate drive is typically referenced to board ground, whereas a high-side gate drive is “floating”.

Low-Side Gate-Drive Measurements

By way of example, first consider low-side gate-drive measurements. The devices being measured are GaN transistors switching with rise times less than 10 ns. These measurements are not as challenging to make as high-side gate-drive measurements, so they serve as a useful comparison of basic performance differences between probes. We’ve made these measurements using four different probe types: a low-voltage 10:1 passive single-ended probe, a high-voltage active single-ended fiber-optic probe (HVFO108), a high-voltage active differential probe (HVD), and a high-common-mode active differential probe (DL-HCM).

If you make low-side gate-drive measurements with these four types of probes, you might get results similar to those shown in Fig. 2, prompting several questions:

1. Why do the passive probe and high-common-mode probe measurements show so much ringing?
2. What causes the pronounced dip in the rising edge of the passive probe and high-common-mode probe measurements?
3. What causes the overshoot on the rising edge of the signal?
4. Why do the high-voltage fiber-optic probe and the high-voltage differential probe show what looks like the best signal fidelity (i.e., no ringing) on the rising edge?
5. Why do the passive probe and high-common-mode probe have the fastest rise times?
6. Why do the high-voltage fiber-optic probe and the high-voltage differential probe not have a very flat top and base?
7. How does probe loading affect the measurements?

(The question numbers in the list above relate to the numbered areas of interest in Fig. 2.)

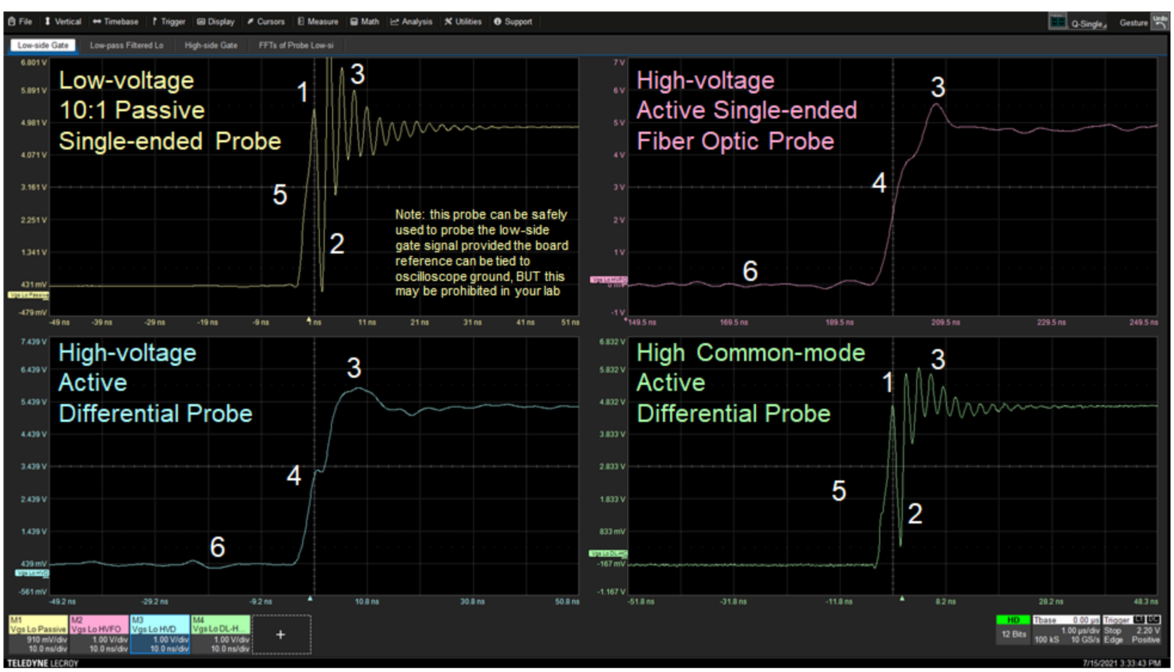

Fig 2. Comparison of measurement results for four probes. Higher bandwidth probes show more ringing.

With respect to the first question, the ringing has approximately a 3-ns period, corresponding to about 350 MHz. The passive probe and high-common-mode probe have higher bandwidths than the others (500 MHz for the passive probe and 1 GHz for the DL-HCM, versus 120 or 150 MHz for the high-voltage probes) and will show more of a signal's native ringing that the lower-bandwidth probes will filter out.

In addition, the probing geometry may make it difficult to probe with high signal fidelity. The distance between the signal and the reference (board ground) may be suboptimal, and the ground and signal connections may form a loop. This is the likely cause of the ringing we see on the higher-bandwidth probes.

Adding a 150-MHz filter to each probe yields the results in Fig. 3, virtually eliminating the ringing on the higher bandwidth probes. This demonstrates that all probes have a similar signal shape when they have similar bandwidths and serves to highlight the subtle differences between the various probe types.

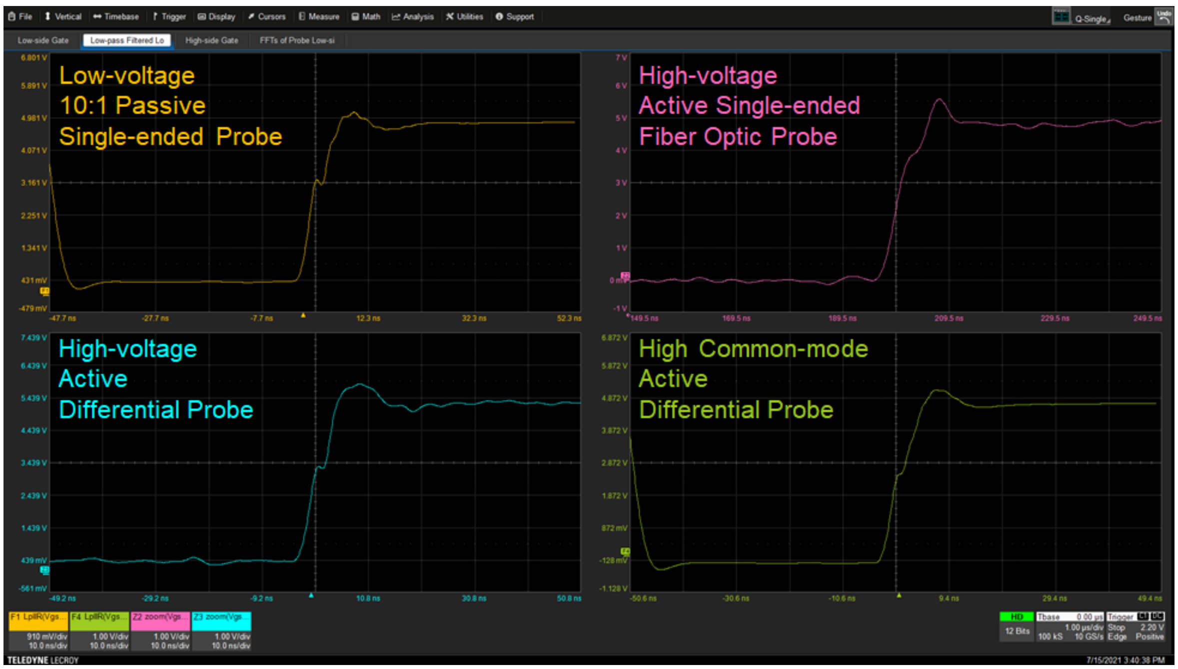

Fig 3. A 150-MHz low-pass filter removes the ringing, making each probe's response comparable.

Regarding question 2, the pronounced dip in the rising edge of the higher-bandwidth probes (i.e., the passive probe and high common-mode probe) is likely due to transient pickup from a high-side device switching moments after the low-side device switches. The CMRR of the (single-ended) passive probe can be inferred to be non-existent, whereas the CMRR of the high common-mode probe is 50 dB at 100 MHz. Thus, the majority of this dip could be attributed to transient pickup from the loop antenna formed by the longer-than-desired test lead that was necessitated by the non-ideal test points.

For the measurements using the high-common-mode probe in Fig. 2, we had to use a 2-in. solder-in tip instead of our preferred high-performance solder-in tip (Fig. 4). This is why it is a good idea to lay out your test points with the goal of minimizing "antennas" created by signal and reference test-point connections. Coaxial connections and short distances are best.

The overshoot issue raised in question 3 could result from one of two factors: the signal being measured has overshoot or the probe contributes overshoot. Regarding the latter, many high-voltage probes have "peaking" designed in near their frequency-response limit, which will result in overshoot or undershoot on very fast rising or falling edges. In general, about 1 dB of peaking will result in a 10% overshoot. Some manufacturers peak their probes by 4 to 6 dB, which for very high frequencies can result in an exceptional amount of overshoot.

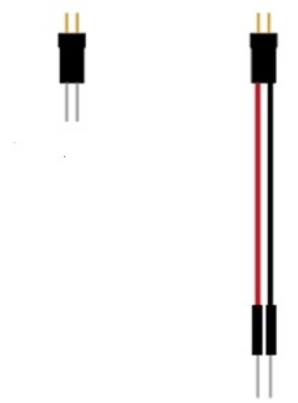

Fig. 4. Shorter leads on the high-performance solder-in tip (left) are preferable; use the 2-in. solder-in tip (right) only if your probing geometry requires it.

The probe lead type and layout geometry can also play a role in peaking, increasing or reducing it. Consult your probe's manual to better understand that particular probe's behavior. Vendors will typically provide a magnitude vs. frequency response curve or a step response plot, often with specific leads or tips referenced, and this can give you an indication about how much overshoot the probe contributes to the measurement. The documentation for the Teledyne LeCroy high-voltage differential probe indicates 0.5-dB peaking at 100 MHz when using the 2-in. solder-in lead, while the high-common-mode probe indicates 0.5- to 1.5-dB peaking at 100 to 350 MHz with same.

Fig. 5 shows the signals from the four probes overlaid to highlight the differences in the probe responses. However, in this view it's hard to separate the ringing from the overshoot.

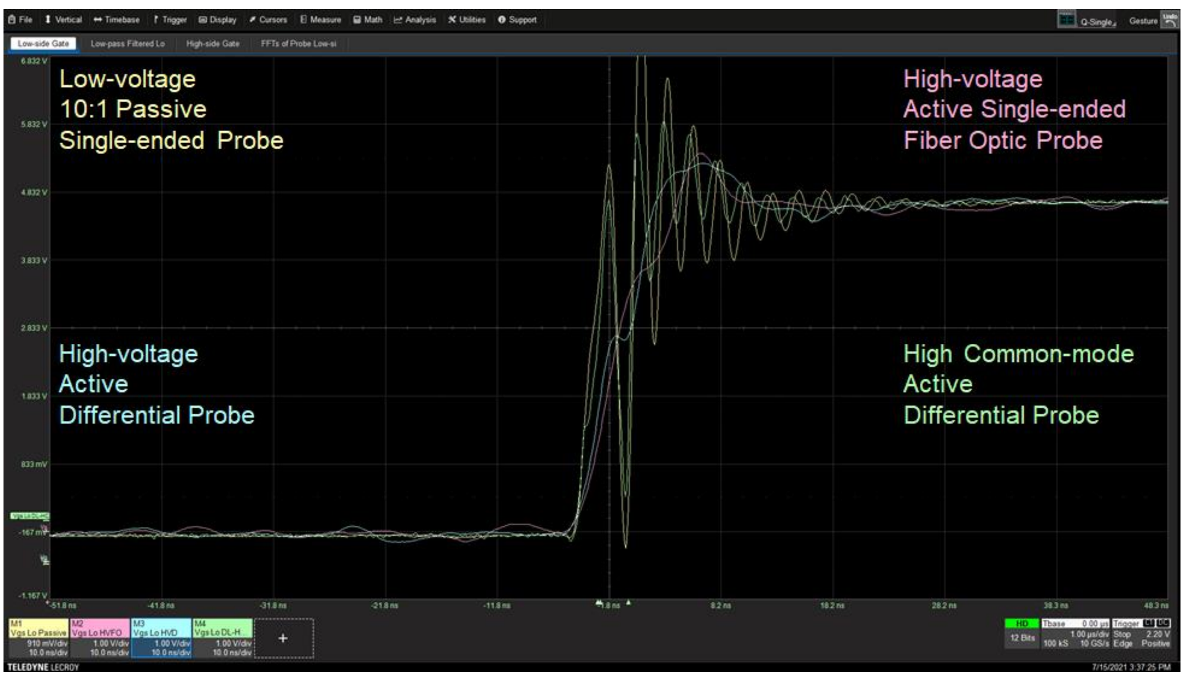

Fig. 5. When the four probe signals are overlaid, it's difficult to separate ringing from overshoot on each.

Fig. 6 shows the same measurements with the 150-MHz low-pass filter applied to each probe, making it easier to see just the overshoot (keeping in mind that the filter will also attenuate some of the overshoot in the probes with higher frequency response). In Fig. 6, all probes show about 10%, or 1 dB, overshoot. Given what we know about probe performance, half of this overshoot is probably due to the probe and half is native to the signal. The HVFO108 is known to peak a little more than the other probes, and this is why its overshoot is the highest.

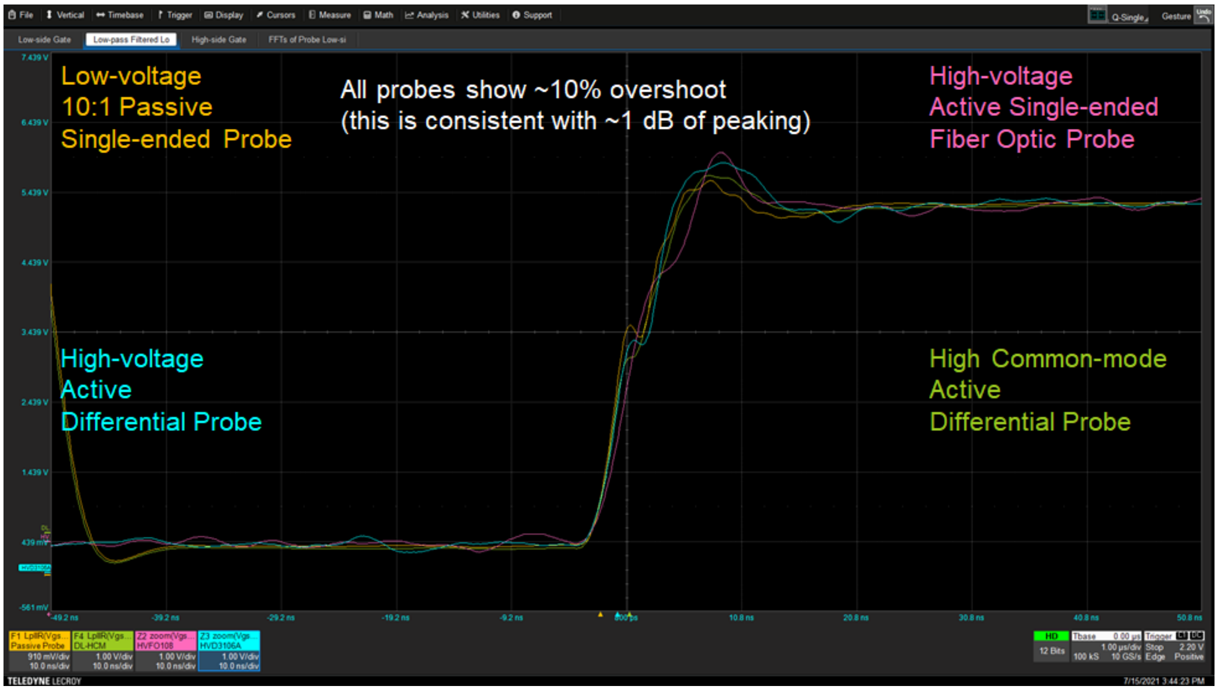

Fig. 6. Overlaid probe signals with a 150-MHz low-pass filter applied all show reasonable overshoot.

Consider questions 4 and 5 together. Why do the high-voltage fiber-optic probe and the high-voltage differential probe have what looks like the best signal fidelity on the rising edge, while the passive probe and high-common-mode probe have the fastest rise times? The answer is simple—the lower bandwidth probes filter out signal content and slow the rise time down, while the higher-bandwidth probes, by design, have faster rise times.

Costs Of Attenuation, Benefits Of CMRR

For question 6, why do the fiber-optic probe and differential probe fail to display the flat tops and bases that the other probes do, the answer is complicated and multifaceted. Some of the effect is due to the noise performance of the probes. Passive probes with 10x attenuation in general have low noise, while active probes with high attenuation will have more noise.

In this case, the high-voltage differential probe has 50x attenuation, the high-voltage fiber-optic probe has 20x, and the high-common-mode probe has only 7.8x. In addition, the fiber-optic probe has a higher (worse) inherent noise floor, while the high-common-mode probe has a very low (better) inherent noise floor.

Furthermore, some of the "noise" on the top and base is due to worse CMRR performance of some probes. High-voltage differential probes can have very good CMRR at higher frequencies, but not as good as the DL-HCM series high-common-mode probe. For 48-V applications, the high-voltage fiber-optic probe's CMRR benefits cannot offset its noise costs. Figs. 5 and 6 are good references to compare the performance of the top and base measurements.

Finally, question 7 asks, how does probe loading affect the measurements? The answer is: it's hard to know in this case because probe loading doesn't seem to be causing issues with proper signal capture (or correct circuit operation)—the shape of the signal is generally very true from probe to probe.

Recall that:

- The low-voltage 10:1 passive probe has a load of 10 MΩ in parallel with 11 pF.
- The high-voltage fiber-optic probe has a load of 10 MΩ in parallel with 22 pF (for a 20x tip).
- The high-voltage differential probe has a load of 10 MΩ in parallel with 2.5 pF.
- The high-common-mode probe has a load of 200 kΩ in parallel with 0.6 pF.

The capacitance value referenced above is the probe tip capacitance. It's possible that the Miller effect voltage plateau appears at higher voltages with probes that have higher tip capacitance (i.e., the passive probe and fiber-optic probe), potentially due to tip capacitance charging time. As shown in Fig. 7, the plateau appears lowest with the high-common-mode probe (lower right), which has the lowest tip capacitance of the four probes, and it appears highest with the fiber-optic probe (upper right), which has the highest tip capacitance. In the image, note the following (as previously discussed):

- The probes with higher bandwidth (passive probe in upper left and high common-mode probe in lower right) are passing the high-frequency content and hence show ringing.
- The ringing is due to a less than optimum layout of test points on the board, which required use of ground leads that acted as antennas for transient noise pickup.

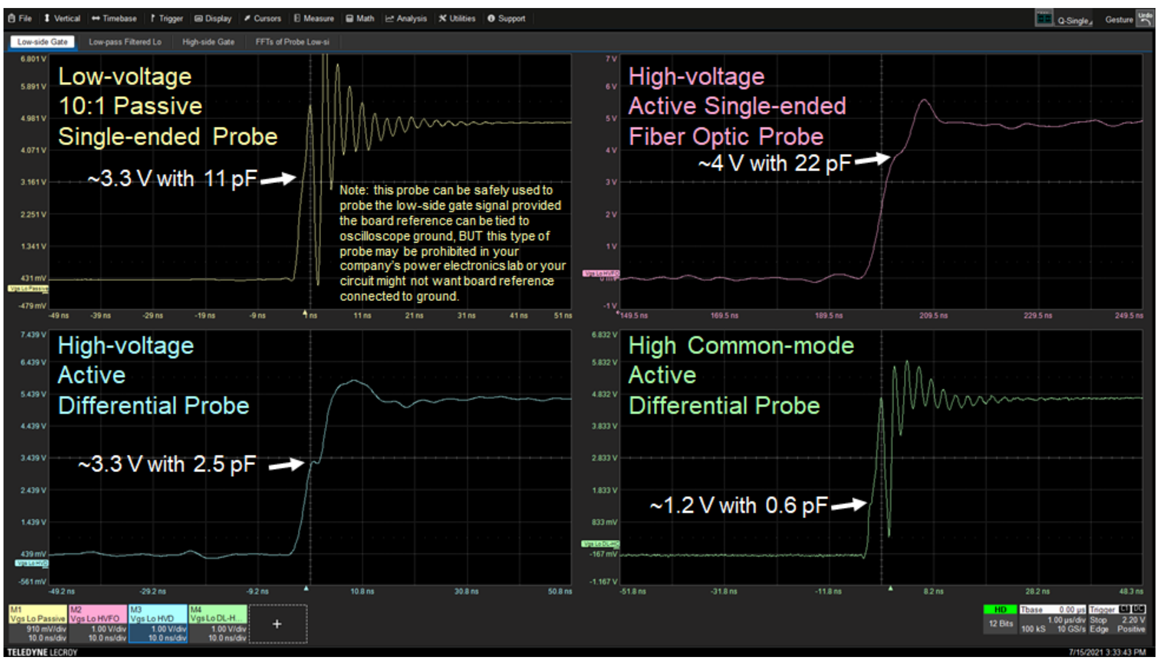

Fig. 7. Probe measurements showing the effect of loading.

High-Side Gate-Drive Measurements

Three of the probes we have been showcasing—the high-voltage fiber-optic probe, the high-voltage differential probe and the high-common-mode probe—can be safely applied to high-side gate-drive measurements on the same GaN devices measured above. This is a more challenging measurement to make as the combination of the floating nature of the signal and the high dV/dt in the signal puts more stress on the measurement probe, exposing probe deficiencies more clearly.

(Note: Do not use a low-voltage 10:1 passive single-ended probe to make high-side measurements. Using the passive probe in this way can damage the probe, the DUT and the oscilloscope, and can cause injury to yourself. Also, do not "float the scope" in an attempt to make high-side measurements. The technique is not safe, and measurement quality will likely degrade. Finally, as we have demonstrated, the passive probe can be used for low-side measurements, but it is not recommended because you may inadvertently probe in the wrong place—some location not referenced to ground. This is the primary reason why many lab managers prohibit the use of low-voltage passive probes in power electronics labs.)

Fig. 8 shows the high-side gate-drive measurement results. In general, the limitations we saw with the high-voltage fiber-optic probe and the high-voltage differential probe during the low-side measurement are more obvious with the high-side measurement.

The architectural benefits (near infinite voltage isolation and great CMRR) of the 150-MHz HVFO108 high-voltage fiber-optic probe (upper right) do not outweigh its drawbacks in the 48-V application space in terms of noise and overshoot. Its CMRR performance can be seen in the very good suppression of the transient pickup from the low-side switching event. However, its bandwidth is not sufficient for GaN measurement applications.

The HVD series high-voltage active differential probe has favorable CMRR and reasonable noise performance for this class of probes, but the stresses imposed on it by the high-side measurement show its limitations, most notably in the transient pickup of the low-side switching event and the more pronounced variation in the amplitude level at the top of the signal after the switching event. Its 120-MHz bandwidth is also not suitable for GaN measurements.

In contrast, the DL-HCM high-common-mode active differential probe (lower right) is optimized for 48-V GaN gate-drive measurements on the high side as well as low side, offering very low noise as evidenced by the very clean top and base. The very favorable CMRR suppresses transient pickup from low-side switching and inhibits interference in the measurement after the switching event. It also has the necessary 1 GHz of bandwidth.

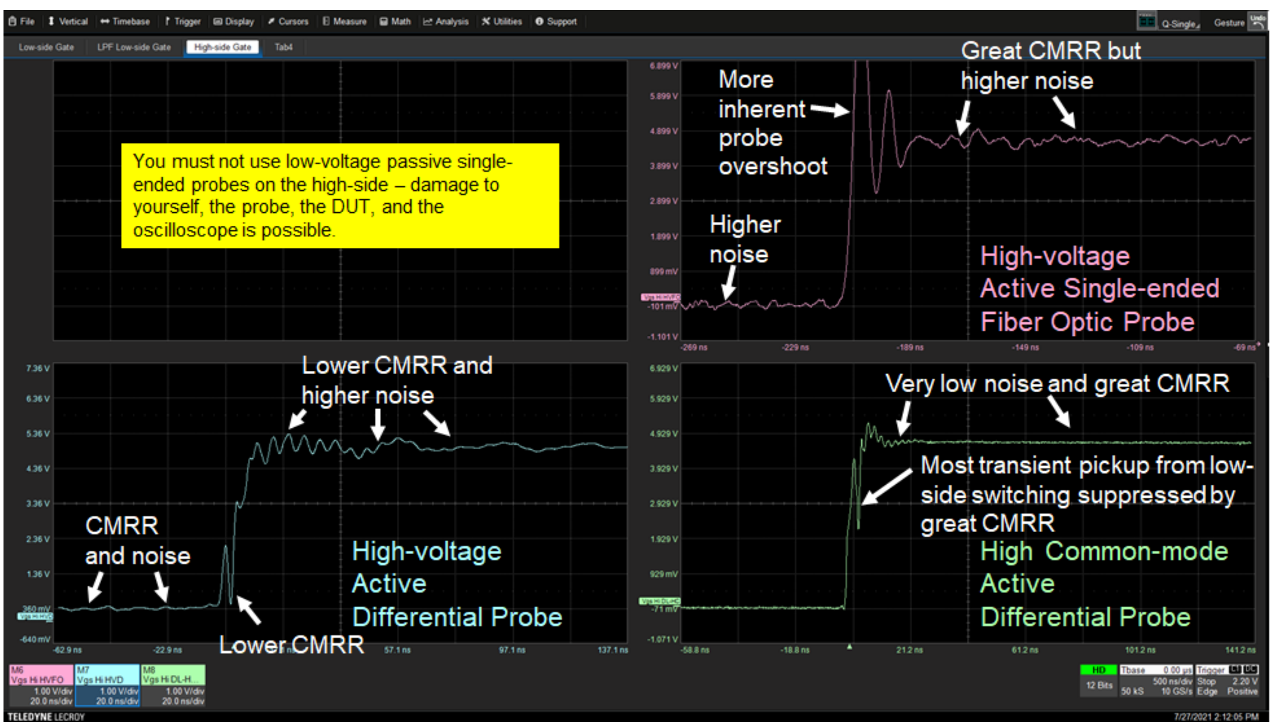

Fig. 8. High-side gate-drive measurement results for three probe types.

Conclusion

In summary, high bandwidth, low noise and great CMRR are all important for precise measurements of GaN devices in the burgeoning 48-V application space. Teledyne LeCroy's DL-HCM high-common-mode active differential probes offer low attenuation and hence low noise, high bandwidth (1 GHz), a very favorable CMRR, and an 80-V_{PP} differential voltage range, making them highly suitable for gate-drive and device-switching measurements in 48-V circuits.

Among the alternatives, high-voltage differential probes with low noise characteristics and good CMRR performance may provide acceptable results, depending on your device, your circuit and your rise times. And high-voltage fiber optic isolated probes can provide the best performance, overall, if they have sufficient bandwidth. However, their prices can be very high, and the characteristics of their design are more suitable for designs with dc bus voltage of 500 V or more.

Reference

This article is adapted from the webinar "Best Practices for 48V Power Conversion Testing" by Ken Johnson and William Kaunds, Teledyne LeCroy. Visit https://teledynelecroy.com/events/ for more information.

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