Narrow Pulse Measurements on Vector Network Analyzers

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***Abstract* - This paper investigates practical aspects of measuring antennas operating with pulsed RF signals of very narrow width, down to 0.1 µs or less. The current generation of network analyzers provides very high IFBW, theoretically allowing measurement of very narrow pulses. But in practice there are several factors that limit the minimum pulse width, including IF path filtering, receiver dynamic range, trigger synchronization issues and test/reference path delays. The paper will compare the performance of both narrow-band and wideband pulse measurements on a Keysight PNA.**

I. Introduction

Antenna measurements sometimes need to be performed using a pulsed RF signal. A pulsed RF signal has a lower average power density than a CW signal, which lowers heat production in chamber absorbers. Many active antennas can only be operated in pulsed mode. The RF system needs to be able to generate and measure the pulsed RF signal that is required for the antenna test.

Pulsed measurements can be made by measuring the CW component of a number of pulses (narrow-band mode) or by measuring the response to a single pulse (point-in-pulse or wide-band mode). Both techniques have their advantages and will be looked at in this paper.

NSI software supports pulsed measurements using VNAs as well as the NSI Panther Receiver [1]. This paper focusses on making pulsed measurements using VNAs, with emphasis on Keysight's PNA. Much of the content applies to the NSI Panther receiver as well.

II. History of Pulsed Measurements

The Agilent 8530A Microwave Receiver supported pulsed measurements using either narrow-band detection or optionally suing wide-band detection (with option H02) [1]. Both versions supported making measurements in either the full pulse characterization region (wide-band pulse mode in today's terminology) or in the high PRF region (narrow-band mode). The minimum pulse width for full performance measurements with the standard 8530A was 180 µs, and for the H02 Wide IF Bandwidth option it was 1 µs. In the so-called peak response region, measurements with reduced sensitivity could be made with the standard 8530A on pulses as narrow as 10 µs.

When the 8530A was succeeded by the first-generation E836x PNA, the minimum pulse width that could be measured in wide-band mode was so wide (>50 µs) that narrow-band pulse mode was required in most cases [3]. The limited pulse width was due to the PNA's low maximum IF Bandwidth of 40 kHz. NSI only supported narrow-band pulse mode for this older PNA.

III. Narrow-Band vs. Wide-Band Pulse Mode

A comparison of Narrow-band and Wide-band pulse mode is shown in Table I.

TABLE I. NARROW-BAND VS. WIDE-BAND PULSE MODE.

Parameter	Pulse Mode	
	Narrow-Band	***Wide-Band***
Number of pulses needed for 1 measurement	Multiple	1
Receiver IF Bandwidth	Low (<< PRF)	High (>1/Pulse Width)
Duty-Cycle Loss (dB)	20 log (duty cycle)	0
Trigger Synchronization to RF pulse	Not Required	Required
CW component extraction (Pulse spectral sidelobe avoidance)	Spectral nulling or High-selectivity IF filtering	Not needed
Cost	$50,000 (PNA options 025, 008)	Ask NSI
Sensitive to Test/Reference delays	No	Yes

In both modes, modulation of the RF pulse may be achieved using option 021 on the PNA, or by using an external PIN switch. If the external PIN switch is located after the directional coupler then a CW reference is obtained.

As indicated by the red highlights in the table, the main disadvantages of narrow-band pulse mode are the duty-cycle loss (pulse desensitization) and the high cost of the PNA firmware option that enables it.

The current generation of PNAs consists of the N522xA PNA and N524xA PNA-X, with virtually identical specifications. They provide a maximum IF Bandwidth of 15 MHz and as a result can support wide-band pulse mode for much shorter pulses, down to 0.1 µs. Table II shows the evolution of the IF bandwidth and minimum pulse width for various PNA models (data provided by Keysight).

TABLE II. PNA IF BANDWIDTH AND MINIMUM PULSE WIDTHS.

PNA model	Maximum IF bandwidth	Minimum pulse width
PNA (E836x) (20, 40, 50, 67 GHz)	40 kHz	50 µs
PNA-L (N5230) (2-port, 20, 40, 50 GHz)	250 kHz	10 µs
PNA-L (N5230) (2-port, 6, 13.5 GHz; 4-port, 20 GHz)	600 kHz	2 µs
PNA (N522x)/PNA-X (N524x) DSP4	5 MHz	267 ns
PNA (N522x)/PNA-X (N524x) DSP5	15 MHz	100 ns

In theory, a reduction of the minimum pulse width to 100 ns does not seem like a big deal. But as the pulses get narrower, a number of issues emerge that need to be dealt with, and that ultimately limit the performance of the RF system.

This paper presents the results of testing done by NSI to verify the RF system performance doing wide-band pulse mode measurements of pulses down to 100 ns pulse width.

IV. WIDE-BAND PULSE MODE IMPLEMENTATION

In wide-band pulse mode the receiver trigger needs to be synchronized to the pulse, but that is easy to achieve. NSI has developed the NSI-RF-5501 Pulse Generator/Synchronizer (PGS, see Figure 1) to support wide-band pulse mode on the PNA without requiring expensive pulse options.

Figure 1. NSI Pulse Generator/Synchronizer

The PGS not only synchronizes the receiver trigger to the RF pulse, but includes a pulse generator as well. Figure 2 shows how the NSI-RF-5501 is used in a system. The PGS is controlled from the measurement workstation using a USB connection.

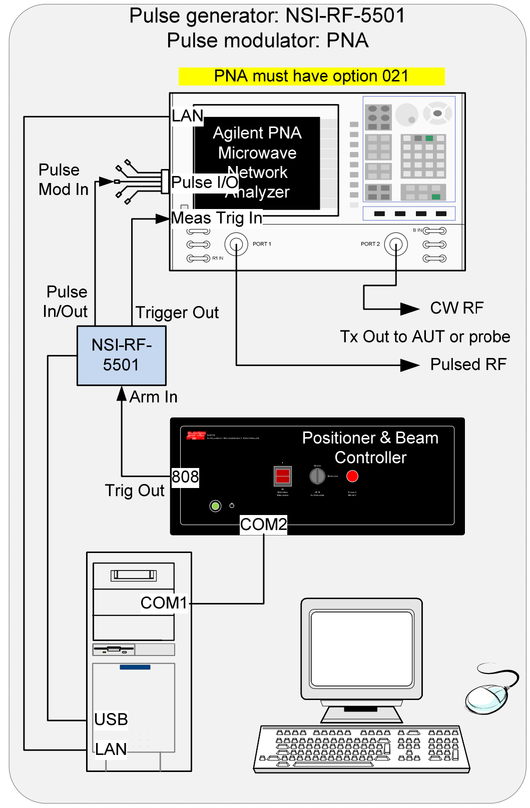


Figure 2. NSI PGS connections

Wide-band pulse measurements do not suffer from duty-cycle loss. But they require that the IF bandwidth is chosen such that the measurement time is less than the pulse width. Figure 3 shows the IF bandwidth that should be chosen for a given pulse width, to satisfy the requirement that the integration time (calculated as 1/(IF bandwidth)) is less than the pulse width.

Note that for point-in-pulse measurements where the measurement is done within a portion of the pulse, the IF bandwidth may need to be higher than shown here.

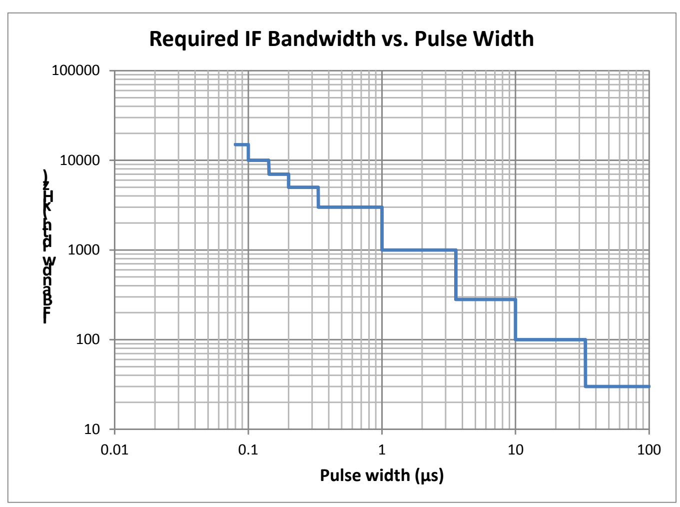


Figure 3. IF bandwidth requirement for wide-band pulse mode

If the pulses are narrow, the high required IF bandwidth results in a significant loss in sensitivity. This is shown in Figure 4 below. This was measured on a 50 GHz PNA at 10 GHz with a 5-ft cable connecting Port 1 to Port 2, at +10 dBm source power. The SNR degrades less than the theoretical SNR degradation of 10 dB per decade, which is also shown (relative to 1 kHz IFBW).

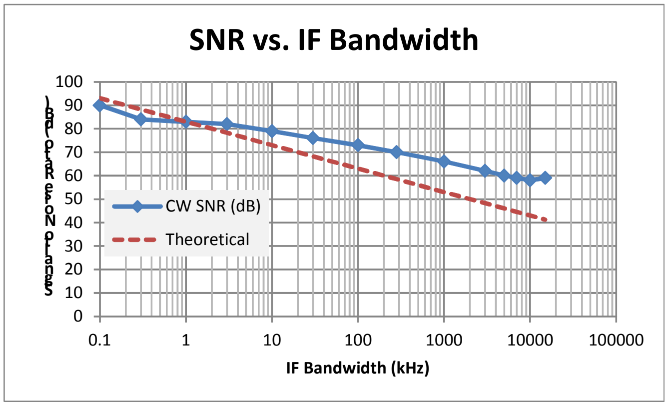


Figure 4. SNR degradation with high IF bandwidths

Note that this loss in sensitivity cannot be compensated by adding amplifiers in the signal path if the signal level is close to the receiver compression level (as was the case here).

Another issue with high IF bandwidths (above 1 MHz) is that the amplitude readout changes with the IF bandwidth, see Figure 5.

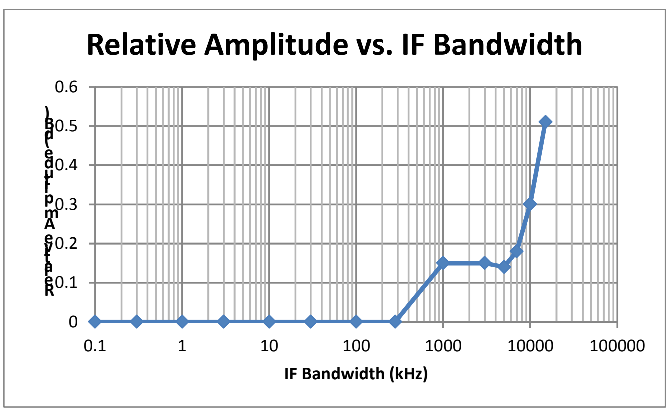


Figure 5. PNA amplitude dependency on the IF bandwidth

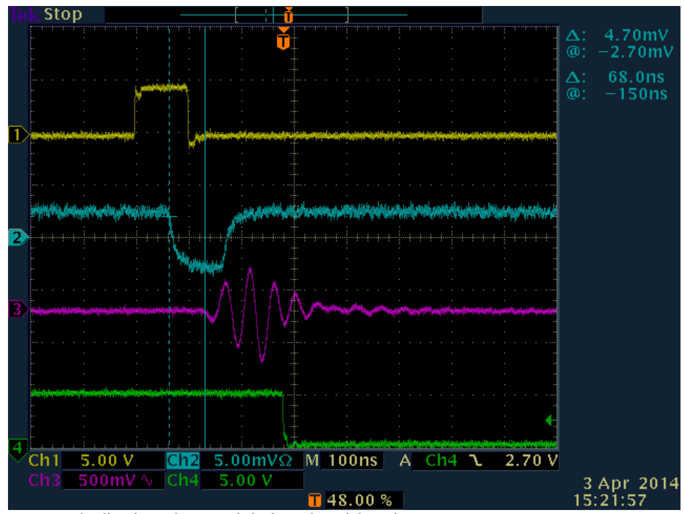
At 280 kHz and below the amplitude readout is independent of the IF bandwidth setting. But at 1 MHz and above, the amplitude changes by up to 0.5 dB when the IFBW is changed. This should be taken into account when doing comparative gain measurements.

V. IF Path Filtering

The RF signal needs to be down-converted to an IF signal before it is received by the VNA or receiver. For a VNA without remote mixers, the down-converter is part of the VNA. In a distributed RF system, external mixers reduce cable losses [4]; in this case the input to the VNA is the IF signal. The Keysight PNA with option 020 allows bypassing the front-end, taking in the IF on rear-panel IF ports. Whether using external mixers or the internal front end, in all cases the IF signal will pass through a low-pass filter (LPF) before entering the receiver A/D converter (ADC).

The rise time of a pulsed IF signal can be affected by the LPF and this can degrade the signal-to-noise ratio. For narrow pulses, the IF filter can severely distort the pulse shape. The standard NSI-RF-5940 Distributed Frequency Converter (DFC) includes a 21 MHz low-pass filter in the IF path. The rise-time of the filter is equal to the reciprocal of the cutoff frequency, $(21\text{ MHz})^{-1}$ = 50 ns. Figure 2 shows the IF waveform of a 100 ns pulse passing through a 21 MHz low-pass filter.

The receiver integration time at 15 MHz IF bandwidth is approximately equal to $(15\text{ MHz})^{-1}$, or 66 ns. The filtered pulse does not achieve a steady amplitude for that duration, and hence the measurement signal-to-noise ratio (SNR) is limited. In this case the SNR was only 13 dB.



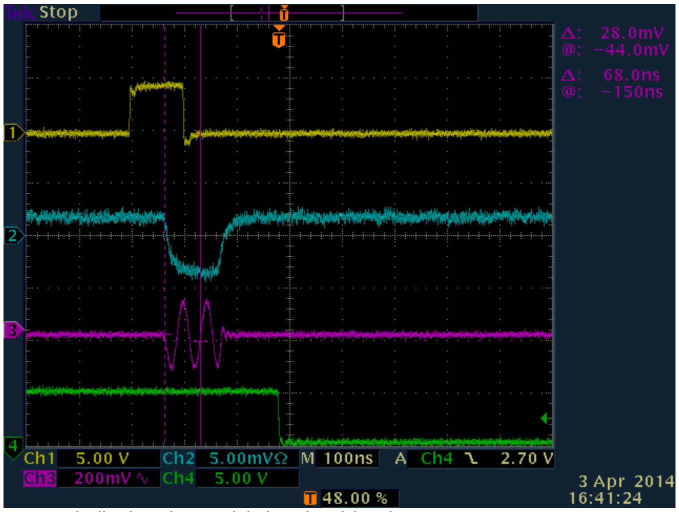
Trace 1 (yellow): Pulse-modulating signal (TTL)
Trace 2 (blue): RF detector output
Trace 3 (magenta): IF pulse after IF filter
Trace 4 (green): PNA trigger

Figure 6. 100 ns pulse passing through a 21 MHz low-pass filter

By replacing the IF filter with a 100 MHz low-pass filter, the pulsed IF waveform was much improved, as shown in Figure 7. The pulse now reaches a steady amplitude, resulting in a signal-to-noise ratio improvement from 13 dB to 37 dB, at 15 MHz IF bandwidth.

Note that the current PNAs, using DSP version 5, have an internal anti-alias filter with a "wide" cut-off frequency setting of 38 MHz which ultimately determines the RF performance in pulse mode.

Also note in Figure 7 below, that the receiver trigger (negative edge on the green trace) occurs after the IF pulse, even though the trigger delay was set for optimal response. The reason is that within the PNA there is a data-processing delay of approx. 250 ns between the receiver input and ADC output [5].



Trace 1 (yellow): Pulse-modulating signal (TTL)
Trace 2 (blue): RF detector output
Trace 3 (magenta): IF pulse after IF filter
Trace 4 (green): PNA trigger

Figure 7. 100 ns pulse passing through a 100 MHz low-pass filter

The 21 MHz IF filter of the NSI DFC places a limit on the minimum pulse width that can be used. Figure 8 shows the SNR vs. IF bandwidth for the 21 MHz and 100 MHz filters.

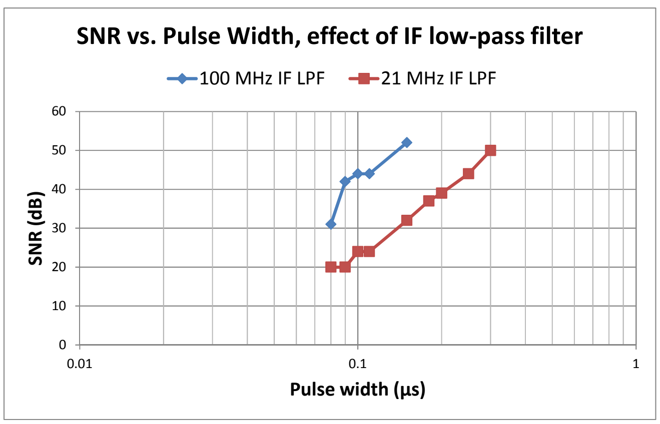


Figure 8. SNR using external converter with 100 MHz and 21 MHz filters

This shows that the standard NSI DFC, which uses a 21 MHz low-pass filter, limits the minimum pulse width to 300 ns. The Keysight 85309B LO/IF Distribution Unit uses a 30 MHz low-pass filter so should allow pulse widths down to approx. 200 ns. NSI offers a DFC "E" variant (NSI-RF-5940E for Extended IF) that supports a 100 MHz IF and it allows a minimum pulse width of 100 ns.

VI. TEST/REFERENCE PATH LENGTHS

As indicated in Table I, wide-band pulse mode is sensitive to length differences between the test and reference path. Since the receiver trigger is applied to both receivers at the same time, the pulse must also be present on both receivers at the same time. This becomes an issue when the pulse width is close to the receiver integration time. The SNR then becomes critically dependent on the receiver trigger delay value that is set in the control software.

Figure 9 shows this effect. The data was taken on a PNA with a 5-foot cable connecting Port 1 to Port 2. The frequency is 10 GHz. For a range of IF bandwidths, the pulse width was reduced to the minimum (as defined in Figure 3) and the SNR was recorded. A large drop in SNR (up to 30 dB) is seen for the shortest pulse width at each IF bandwidth setting.

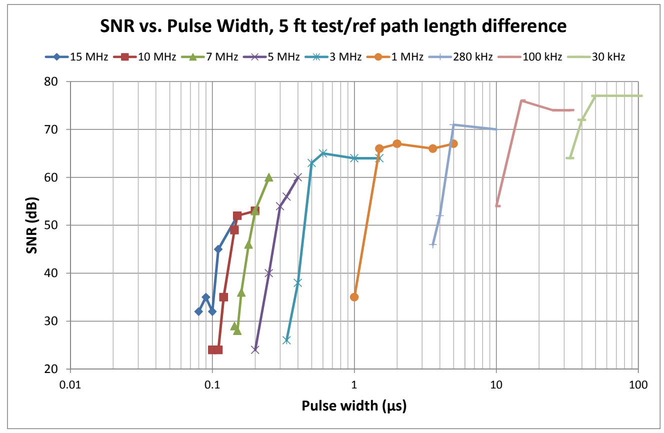


Figure 9. SNR vs. pulse width with unequal test/ref path lengths

In this Figure, for each data point the pulse trigger delay was adjusted for maximum SNR. Even a small change of 10 ns in the trigger delay can result in significant differences in SNR.

When the test and reference path lengths were made equal by inserting a 5-ft cable in the PNA reference loop, the SNR degradation was significantly smaller, see Figure 10.

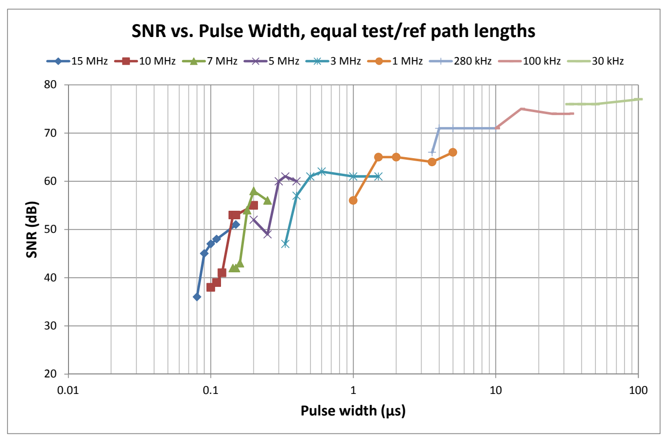


Figure 10. SNR vs. pulse width with equal test/ref path lengths

The larger the antenna measurement facility is, the more likely there will be a large length difference between the test and reference channels. Also, the length difference will vary with different range modes (AUT Tx or AUT Rx). In this case it is essential to monitor the IF pulses on an oscilloscope and insert cables in the IF or RF path to ensure the pulses arrive at the PNA at the same time.

The above chart can be used to select the IF bandwidth that produces the highest SNR at the pulse width of interest.

When using an NSI Panther 9000 receiver, the SNR will also be reduced for narrower pulses. However, the NSI receiver has the advantage that it can perform averaging that is synchronized to the pulse. It can do multiple integrations per pulse if the pulse width allows, and integrate over multiple pulses as well.

VII. WIDE-BAND PULSE MODE ON LARGE SCANNERS

For large planar near-field scan sizes, the RF path length of the test channel changes with probe position. This will cause a variable delay of the test channel pulse. If the reference channel is also pulsed, and the pulse width is the same as or close to the integration time, then the variable pulse delay may start to degrade the signal. To avoid this, the scan size may need to be limited.

To make sure the test channel pulse does not move outside the measurement window, it should be verified using an oscilloscope that the test channel pulse starts before the receiver integration time starts by a time that accommodates the varying delay. An easier way to do this is given by these steps:

1) Determine the receiver trigger delay that gives the highest SNR,
2) Reduce the delay by the amount of time corresponding to the furthest probe travel, and verify that the SNR is still acceptable,
3) Set the delay back to the first value.

The relation between probe travel distance and time delay is given by $t = s/c$, where t is time, s is probe travel distance and c is the speed of light.

If the scan size is so large that no suitable range of trigger delays is available for the given pulse width and IF bandwidth, a CW reference must be used.

Using a CW reference means the pulse-modulating switch must be located past the directional coupler that provides the reference signal. In most cases on large systems, the coupler will be located close to the AUT or on the probe carriage of the scanner. Adding a remote pulse-modulating switch will add complexity to the RF system and reduce the dynamic range by the insertion loss of the switch.

On the other hand, if wide-band pulse mode can be used then we have found that the performance difference between a CW and pulsed reference is negligible, even if the pulsed RF signal passes through amplifiers and frequency multipliers.

VIII. OPTIMIZING DYNAMIC RANGE

With less than 50 dB SNR available on a standalone PNA with 5 ft cable length (at 100 ns pulse width in wide-band pulse mode), once the transmission loss between the AUT and probe and the losses of longer cables are added, one would think that the SNR would end up being too low to measure anything. This is where the benefits of using a distributed RF system kick in [4]. With an available RF power level of typically 18 dBm at 40 GHz and a maximum mixer input signal of -17 dBm (in 3^{rd} harmonic mode), the minimum RF path loss is 35 dB. As long as the path loss (transmission loss plus cable loss) is less than 35 dB, there will be no reduction in dynamic range at all.

Maximizing the dynamic range may include operating the mixers close to their actual compression level, which is higher than the specification level. This includes maximizing the reference mixer power level. The standard NSI amplifier-multiplier-coupler assembly (model NSI-RF-58x0, see Figure 11) includes a large enough internal reference attenuator to cover the entire 1 GHz to 50 GHz range. To allow adjusting the reference attenuator, NSI can supply the assembly without internal reference attenuator (“A” option).

Figure 11. NSI-RF-5850 Amplifier-Multiplier-Coupler Assembly

CONCLUSIONS

For pulse measurements in PNA wide-band mode, the following guidelines apply:

- The minimum recommended pulse width is 200 ns. Below that, narrow-band mode gives better results
- Wide-band mode can be used down to 100 ns pulse width if amplitude levels are optimized, test and reference path lengths are equalized and the frequency converter uses >38 MHz low-pass filters (such as the NSI DFC with extended-IF option).
- A “standard” frequency converter with 20 MHz low-pass filter allows using wide-band pulse mode with pulse width greater than 300 ns.
- Depending on the pulse width and IF bandwidth being used, the test and reference path length may have to be carefully equalized.
- On large planar near-field systems using wide-band pulse mode with narrow pulses and a pulsed reference, the pulse width may need to be increased to allow for varying pulse timing due to probe motion.
- To optimize the power levels on a distributed RF system, operate both the test and reference mixers as close as possible to the compression point.
- For gain measurements at IF bandwidth of 1 MHz and above, the same IF bandwidth should be used for the AUT and gain reference measurement.

REFERENCES

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[5] Agilent Application Note “Active-Device Characterization in Pulsed Operation Using the PNA-X”, Publication 5990-7781EN