

Keysight Technologies

Low-Frequency Noise Measurements with the E4727A and Their Applications

Application Note



Unlocking Measurement Insights

Introduction

Introduction to Noise and Noise Modeling

Any undesirable turbulence that corrupts an information-bearing signal is generally referred to as noise. Electrical noise is inherent in every circuit, ranging from current flowing through a resistor or transistor, to leakage current through a tantalum capacitor. To minimize its effects, it becomes necessary to measure and quantify the noise of the constituent parts, and then connect the constituent noise contributions to overall circuit performance. In the case of a voltage-controlled oscillator, transistor noise results in small frequency fluctuations measured as phase noise. In the case of a low-noise amplifier or an operational amplifier circuit, resistor noise in the feedback can greatly increase the resultant voltage noise at the output. A typical amplifier will not only amplify the signal and noise at the input (which is desirable), but also contribute its own noise (which is undesirable).

The E4727A Advanced Low-Frequency Noise Analyzer (A-LFNA) enables a closer, deeper look at noise. A device designer may extract noise models using powerful device modeling software like the Model Builder Program (MBP) and the Integrated Circuit Characterization and Analysis Program (IC-CAP). The models may be then passed along to circuit designers, who may then push the envelope in low noise circuitry.

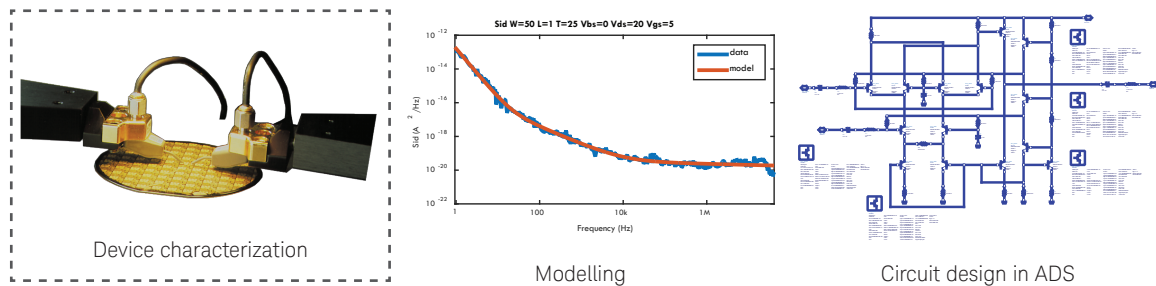


Figure 1. High-level flow of information from device characterization to modeling to low-noise circuit design.

The E4727A addresses the first function shown in Figure 1: noise data measurement. In this application note, we will cover the following topics:

- Basics of noise spectral density
- Noise measurement applications
- Practical considerations in noise measurements
- How the E4727A addresses noise test challenges

Understanding Noise Power Spectral Density

Noise may be quantified in terms of its aggregate effect in the time domain, as in peak to peak fluctuations about some mean voltage, or in terms of its standard deviation about some mean voltage (RMS). Underlying these time domain manifestations is the frequency content of the voltage fluctuations, which is expressed as voltage (“en”) or current (“in”) spectral noise density with units of either $V/\sqrt{\text{Hz}}$ or $A/\sqrt{\text{Hz}}$. In order to discuss RMS noise power, it is imperative to describe the bandwidth over which one would integrate the spectral density.

There are two noise spectral density shapes that capture the vast majority of electronic device noise modeling situations.

1. White noise, where the spectral content is flat versus frequency. This is always present.

$$en = en_white$$

$$in = in_white$$

2. $1/f$ or flicker noise (also known as “pink noise”), where the spectral density is inversely proportional to the frequency.

$$en(f)^2 \left(\frac{V^2}{\text{Hz}} \right) = \frac{Kv^2}{f} \qquad in(f)^2 \left(\frac{A^2}{\text{Hz}} \right) = \frac{Ki^2}{f}$$

The two scenarios are pictured in Figure 2.

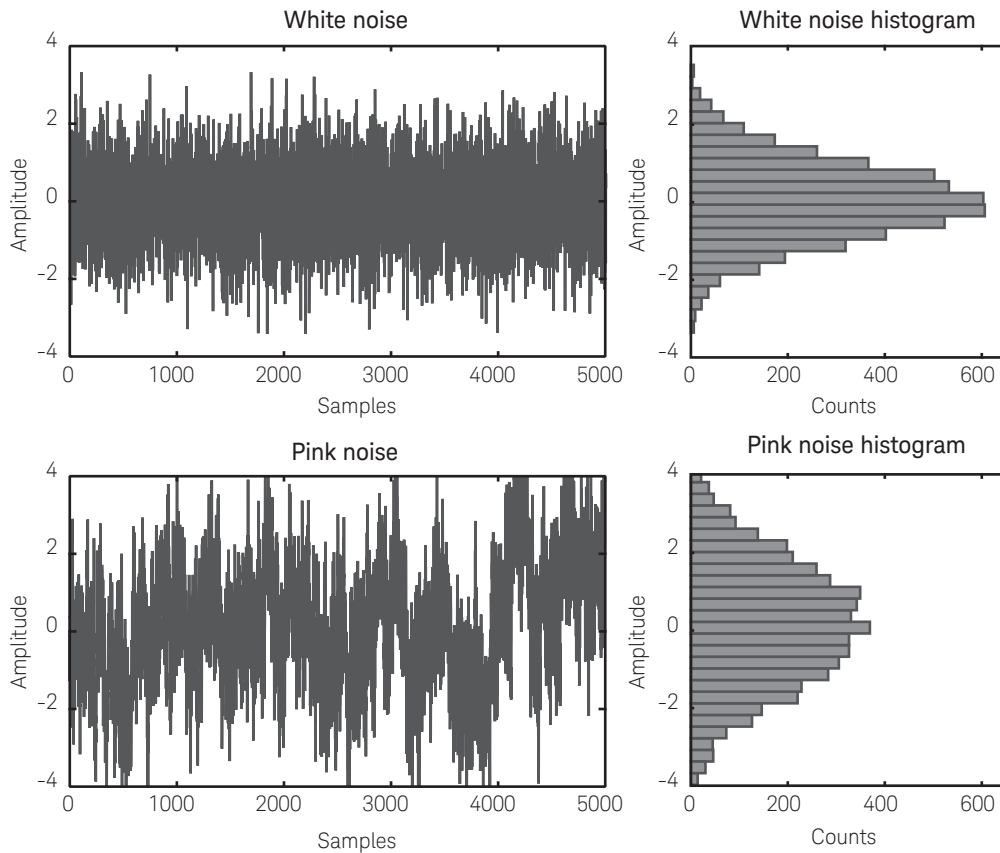


Figure 2. Example time domain data of white noise and $1/f$ noise.

The histograms shown to the right in Figure 2 show a more peaked distribution for the white noise as compared to pink noise. Another type of noise that results in a bimodal distribution is random telegraph noise (RTN), also known as “burst” or “popcorn” noise. With RTN, sudden step-like transitions between 2 or more levels are observed, as shown in Figure 3.

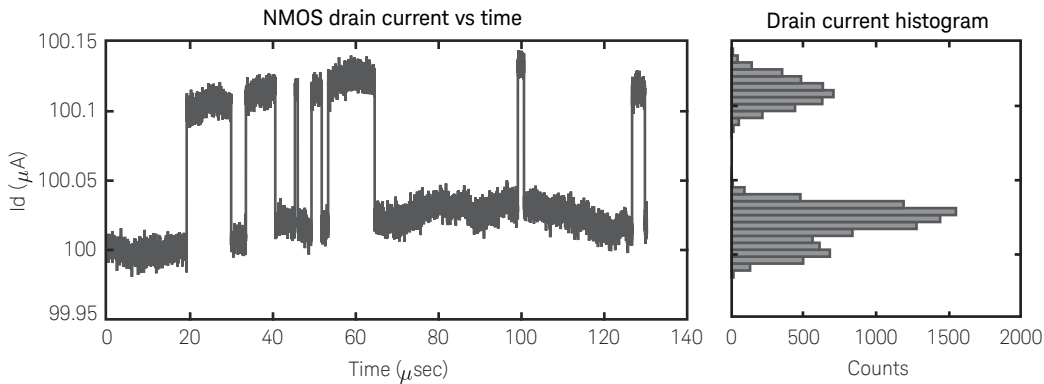


Figure 3. Example NMOS drain current in the time domain showing random telegraph noise (RTN).

Figure 4 presents a typical measurement scenario showing both 1/f and white noise.

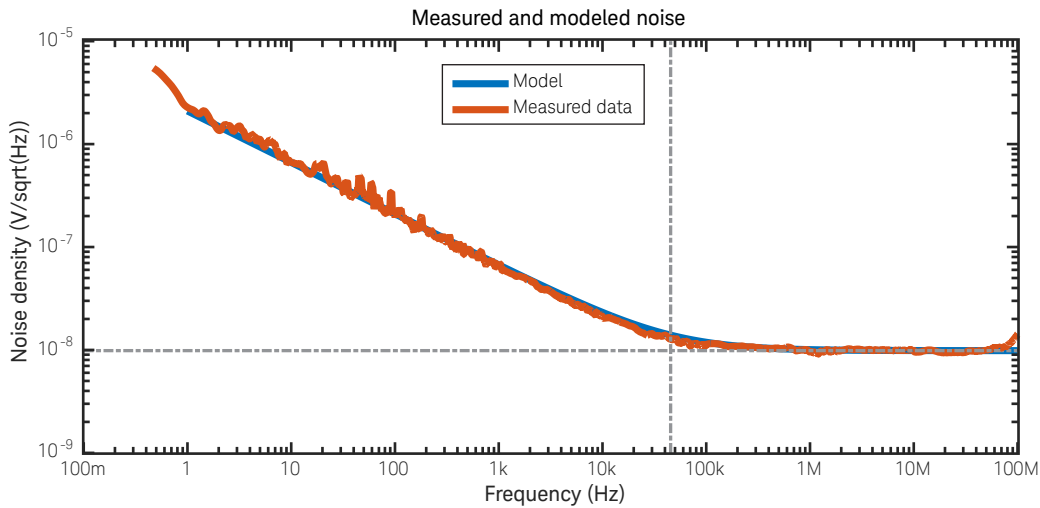


Figure 4. Measured noise power density showing 1/f noise and white noise.

The two effects are presented in the following equation, which was fitted to the above data.

$$\text{Noise}(f) = 20 \cdot \log \left(\text{Noise_Floor} \cdot \sqrt{1 + \frac{\text{Corner_Freq}}{f}} \right)$$

The extracted noise floor is 9.8 nV/√Hz, and the corner frequency is 45.3 kHz.

There is a strong similarity between the equation above and the way that SPICE models noise current in a diode².

$$I_d(f)^2 = \frac{KF \cdot I_{dc}^{AF}}{f^{EF}} + 2 \cdot q \cdot I_{dc}$$

The parameters AF, KF and EF typically need to be fitted to the measured data. In particular, EF may be used to set the slope with respect to frequency. If we initially assume EF = AF = 1, then the observations on current noise floor and 1/f frequency may be combined with the above equation as follows².

$$I_{dc} = \frac{\text{Noise_Floor}^2}{2 \cdot q} \quad \quad KF = 2 \cdot q \cdot \text{Corner_Freq}$$

Building on this, the modeling engineer will model current noise as a function of DC bias and device size. The noise data from the E4727A is easily ported to noise modeling software like MBP or IC-CAP, thus streamlining the model process.

Noise Measurement Applications

Across the electronics industry, the need to characterize noise is ubiquitous. Wherever there is a sensor, detector or receiver accompanied by signal processing circuitry, numerous impairments are possible – both systematic and stochastic. While the systematic errors can often be calibrated out, the noise floor sets an absolute level to the sensitivity of the detector circuit. Noise considerations are also important on the signal-creation side. For example, an ultralow noise voltage reference circuit provides a temperature stable bias voltage that may be applied to a digital to analog converter (DAC), the active element inside a low noise oscillator, a low noise amplifier (LNA), or even industrial process control circuitry that provides programmable voltage and current outputs. By influencing voltage thresholds or timing jitter, voltage noise can easily translate to amplitude noise or phase noise in an RF communications signal, leading to degraded modulation quality. The following provides more details on two applications where high voltages or very low frequency noise data are required.

Application: GaN Devices for Radar Transmitters

To resolve the locations and velocities of unfriendly targets, high-power transmitters are required in radar systems and weather tracking systems. A typical radar transmitter - receiver block diagram is shown in Figure 5. The high-power amplifier (HPA) has been implemented using solid-state laterally diffused MOS (LDMOS) devices.

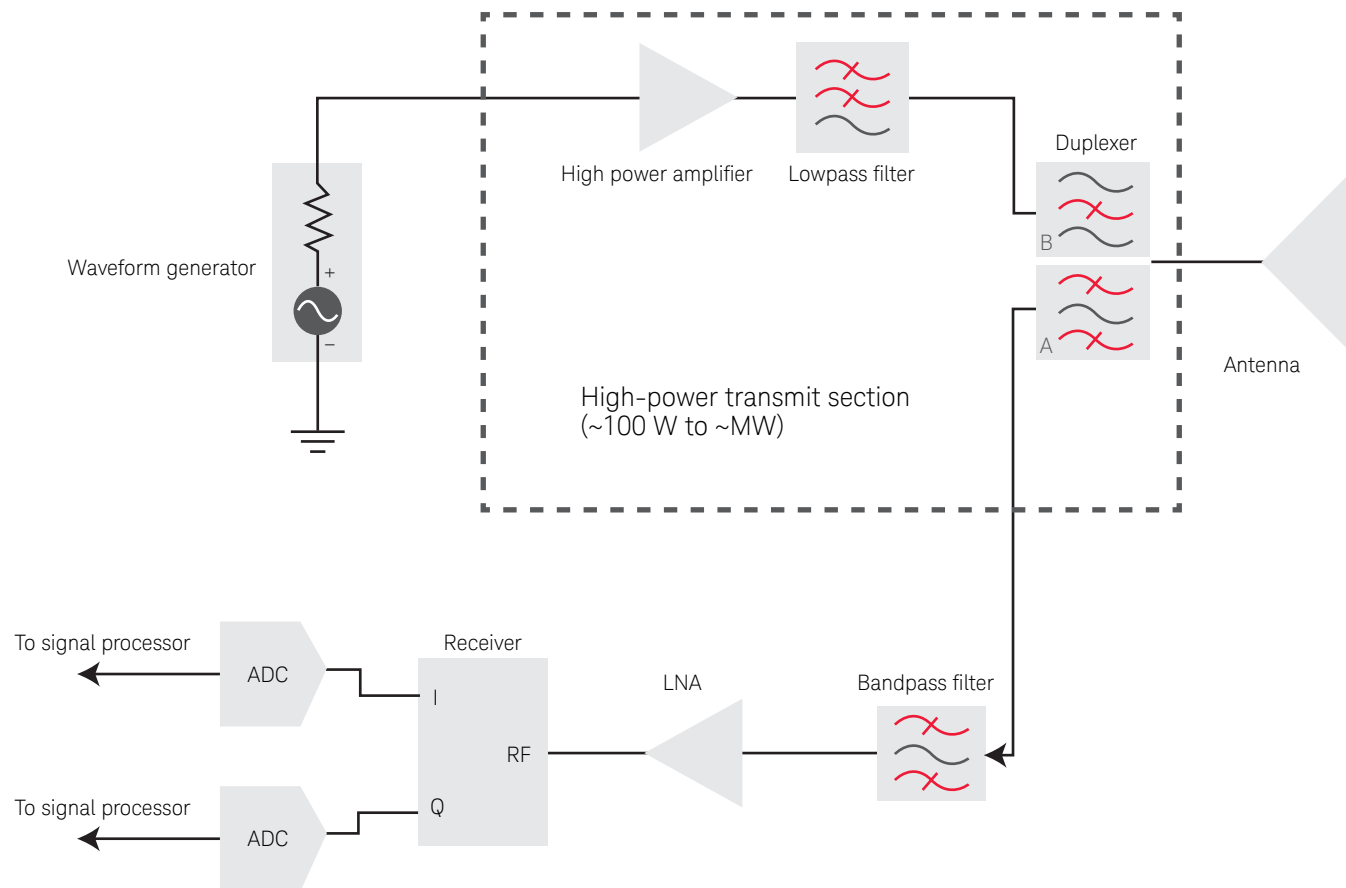


Figure 5. Simplified radar transmitter/receiver system block diagram.⁶

GaN devices have recently attracted significant interest for high power RF amplifiers due to their high electron mobility, high breakdown voltages and excellent reliability at elevated temperatures.³ However, the high-power amplifier must be both rugged and low noise. Broadband noise and 1/f noise of the final stage device modulates onto the carrier, causing an overall degradation to the received signal-to-noise ratio. Pulse-Doppler radar enables the detection of both location and velocity based on the timings and frequency shifts of the echoes received. The frequency spectrum near the carrier is estimated from these echoes by FFT analysis. For a small, slowly moving target, the Doppler shift will be small, making it difficult to separate the target from the close-to-carrier noise of the radar. As shown in Figure 6, target 2 is a low amplitude target with a small frequency shift that can easily be overshadowed by the phase noise sidebands of the transmitter signal or receiver LO.

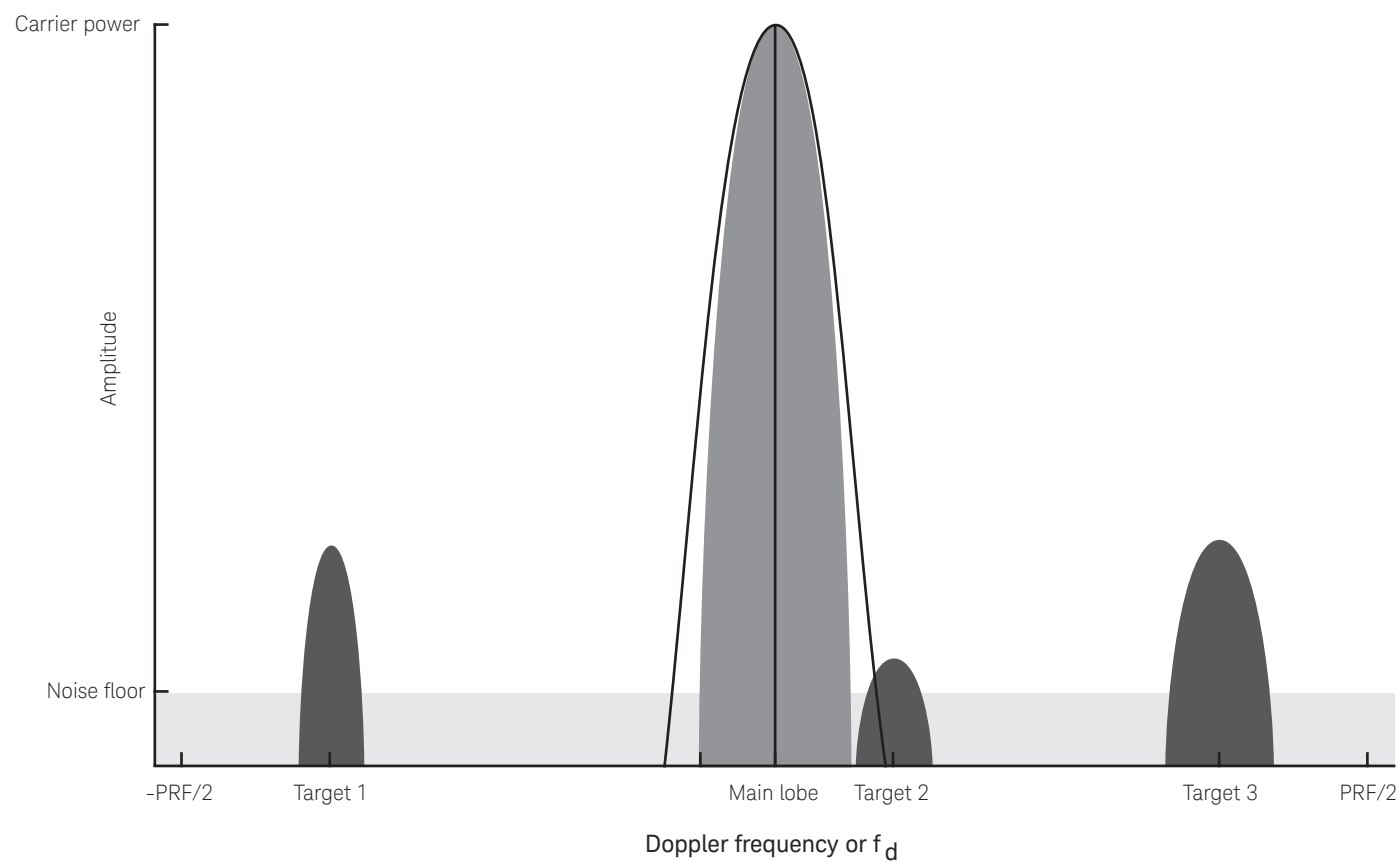


Figure 6. Doppler shift exhibited by 3 moving targets. With the noise floor and 1/f noise on the main lobe, radar return clutter can mask target 2.

The E4727A leads the industry in its ability to handle output voltages of up to 200 V, making it well suited to the characterization of GaN, SiC and other high-voltage devices.

Application: Optical Image Stabilization

Optical Image Stabilization (OIS) technology in handheld digital cameras is effective in mitigating the effects of involuntary movements of the hand. This movement inevitably results in unwanted blurring. Major developments in the market have made this an increasingly important technology.⁴ Since 2010, digital still cameras have been steadily replaced by smart phones that feature large LCD displays and built-in digital cameras. The cameras are manufactured with increasingly smaller size, lighter weight and higher resolution. Lighter cameras result in greater blurring, an effect that is further exacerbated by the use of selfie sticks and users taking pictures with one arm outstretched. With image stabilization, the user may feel free to increase the exposure time in low light conditions. Earlier digital image stabilization (DIS) methodology involved elaborate and computationally intensive software to shift an image during the photo shoot so as to counteract the effects of hand motion. More recently, camera manufacturers are shifting to OIS, which senses and counteracts the movements of the lens itself. This is enabled by three key components at the heart of a typical lens shift scheme.

- Two MEMs-based gyroscopes are used to measure the rate of rotation in terms of yaw (bearing) or pitch. The voltage output is digitized and integrated to get angle of rotation.
- Two Hall-effect magnetic sensors are used to measure the displacement of the camera lens relative to the chassis or cell phone.
- Voice coil motors (VCM) are used to actuate the movement of the lens to track the position of an image.

The OIS control loop block diagram is shown in Figure 7. Assuming the mobile phone is oriented vertically with the camera on its backside, any aberrations in camera direction along the horizon will be picked up by the “yaw” gyroscope. Any vibrations in tilt will be picked up by the “pitch” gyroscope. Spiral movements of the camera would be considered “roll” movements and these are not corrected.

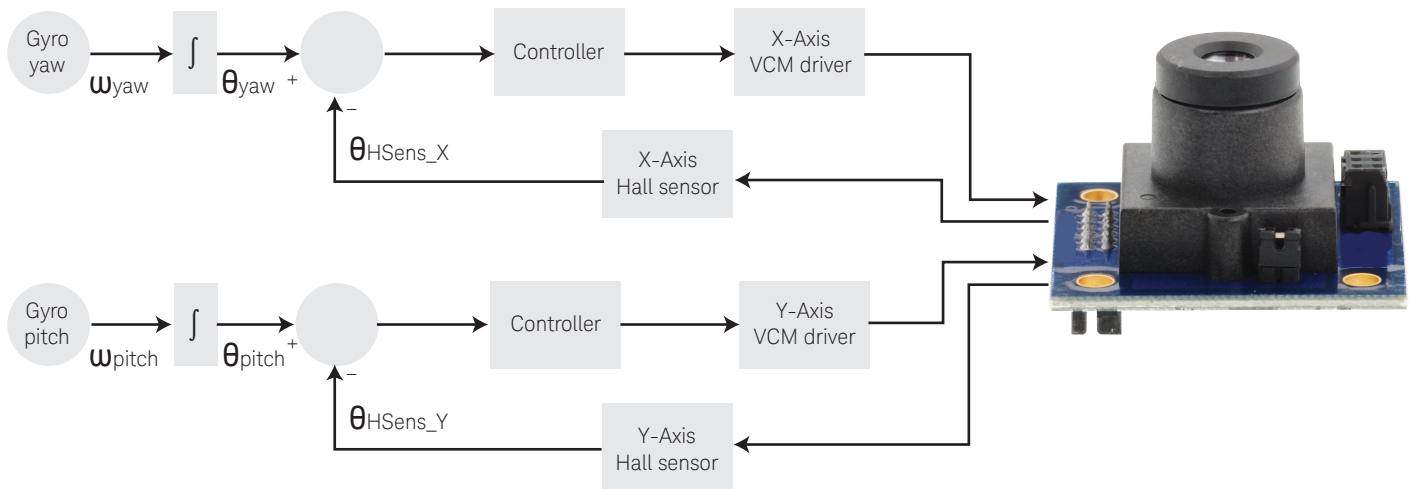


Figure 7. Optical image stabilization control loop block diagram.⁴

The gyroscopes, magnetometers, and their associated post-processing circuitry must each be of low enough noise so as to not corrupt the operation of the control loop. Manufacturers represent gyroscope noise density as “dps/√Hz” or angular rate (in degrees) noise power density. Magnetometer noise density is represented in “nT/√Hz.” The frequency range for this characterization must extend below 1 Hz, as shown by hand tremor data presented in Figure 8.

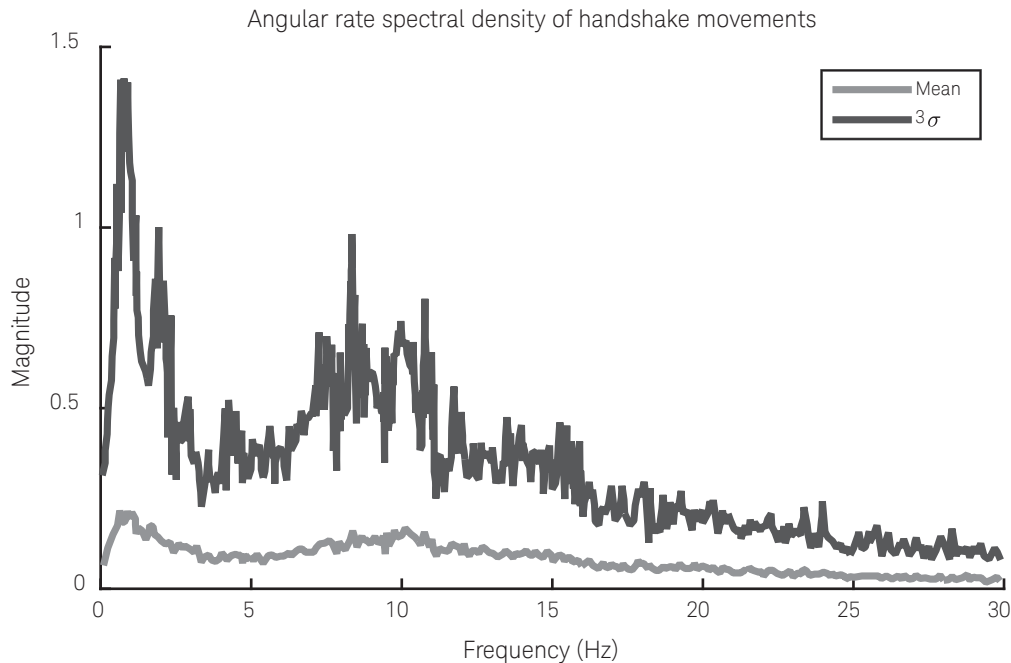


Figure 8. Angular rate spectral density of handshake movements.⁴

The E4727A uniquely enables measurements down to 0.03 Hz, making it well-suited for noise characterizations on image stabilization systems.

Practical Considerations in Noise Measurements

One of the biggest challenges in measuring component noise is avoiding data corruption by other noise sources in the system. Each of these noise sources will add in a root sum of the squares (RSS) fashion, meaning that two independent noise densities of equal power will add to give rise to a 3 dB increase in the overall noise.

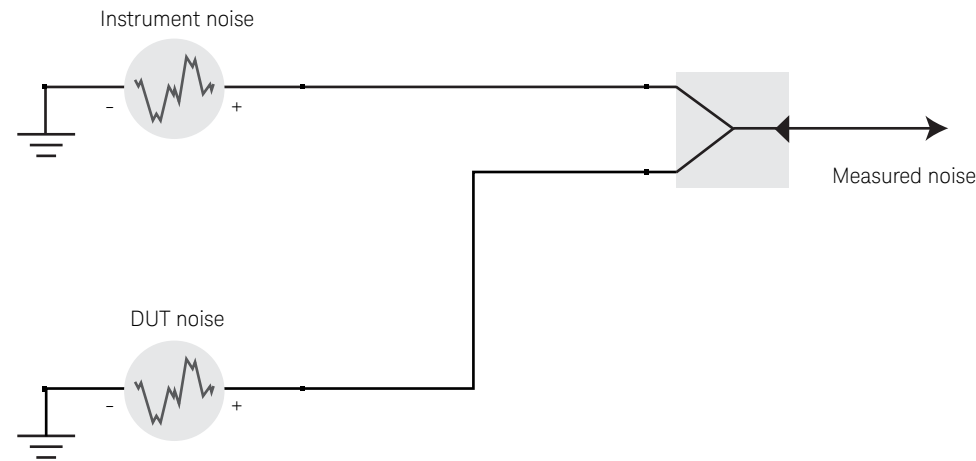


Figure 9. Illustration of instrument reference noise and noise from device under test.

The noise density of the measurement system must be significantly better than the device under test (DUT) so as to not overestimate DUT noise. Figure 10 presents the apparent error that may occur when the DUT noise is close to the system reference noise at any given frequency.

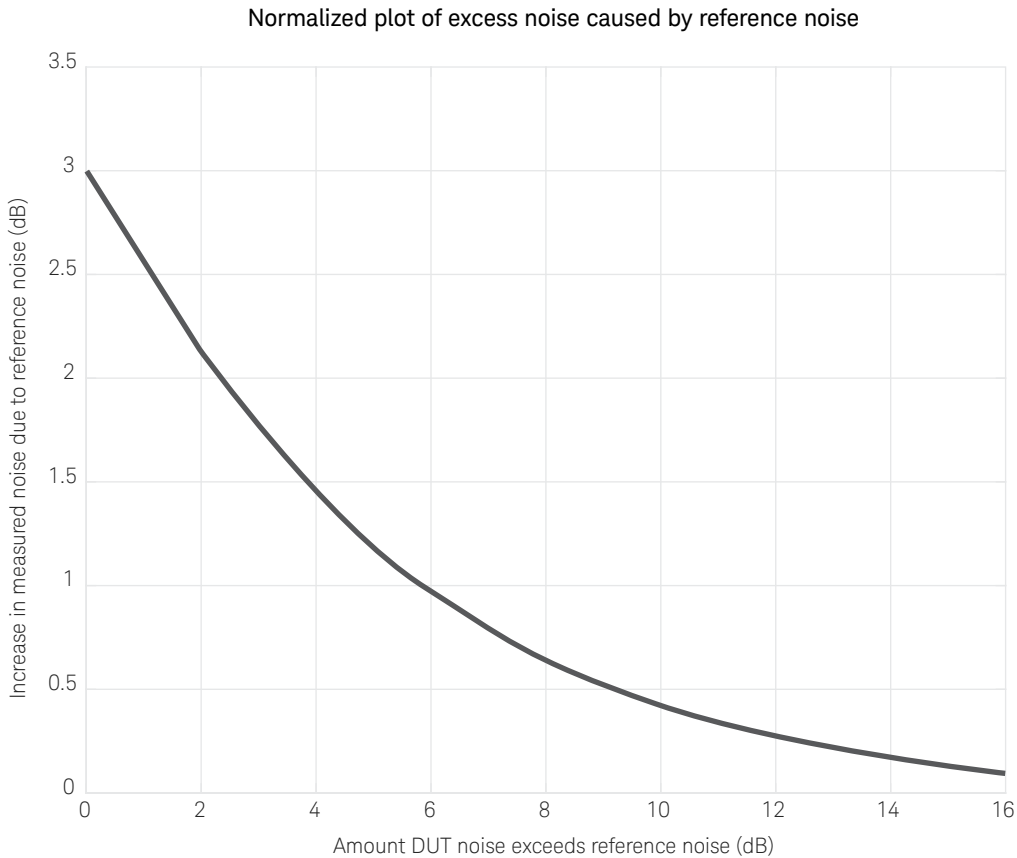


Figure 10. Increase in measured noise due to reference noise being close to the DUT noise.

The amplifier VAMP illustrated in Figure 12 amplifies the low-level noise signals so that the digitizer may accurately represent the spectral density, thus capturing device noise density. Since the noise of this amplifier adds in an RSS fashion to the noise of the device under test, the additive noise of the amplifier becomes a critical specification for sensitivity. The previous generation 1/f noise measurement system amplifiers proved inadequate for some devices. The latest E4727A features a newly-developed amplifier with $-183 \text{ dBV}^2/\text{Hz}$ floor (equivalent to the noise of a 28Ω resistor) and a corner frequency of only 20 Hz (Table 1). Figure 11 presents the additive voltage noise of the LNA in the latest E4727A as compared to its predecessor, the E4725A. We find that the E4727A has a much lower noise density, enabling industry-leading measurement sensitivity and modeling accuracy.

	E4725A	E4727A
Noise floor	$-177 \text{ dBV}^2/\text{Hz}$	$-183 \text{ dBV}^2/\text{Hz}$
	$1.4 \text{ nV}/\sqrt{\text{Hz}}$	$0.67 \text{ nV}/\sqrt{\text{Hz}}$
Corner frequency	10 kHz	20 Hz

Table 1. Tabulated LNA performance of predecessor E4725A and current E4727A measurement system.

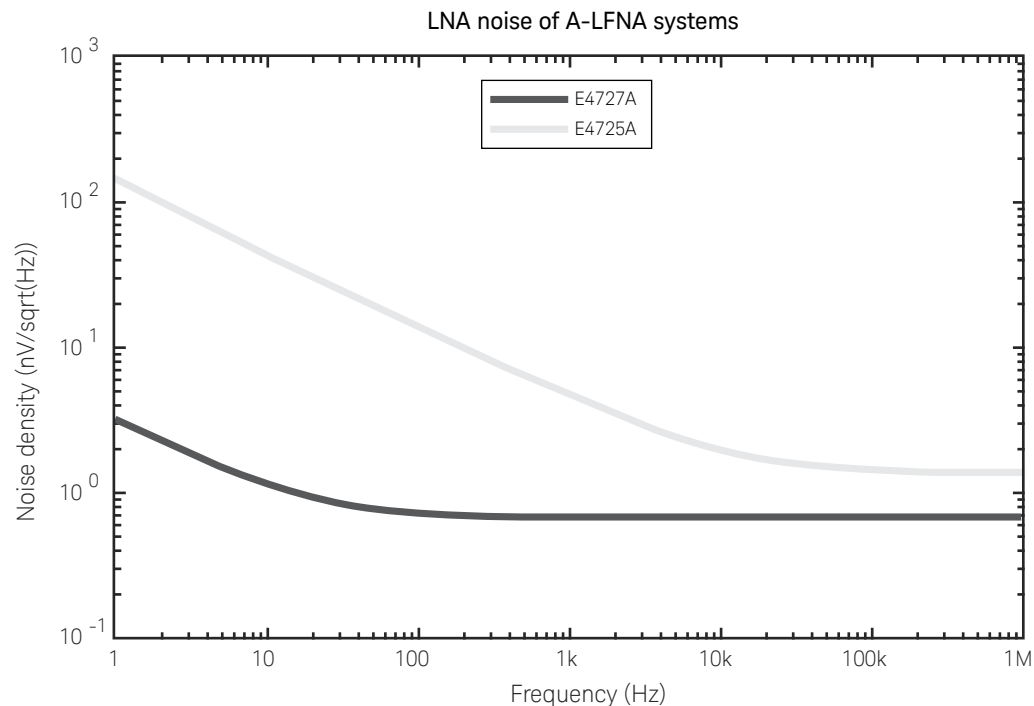


Figure 11. Noise floor comparison of E4727A and E4725A A-LFNA systems.

The additive noise of the amp preceding the digitizer is one important contributor to system noise, but careful attention must be paid to other noise sources, including the following:

- Noise from the power supplies used to bias the DUT. On an MOS device, this could include connections to the substrate or gate.
- Thermal noise from resistors used to set source and load impedances to the device under test.
- Coupling of Earth ground noise to instrument chassis. Besides connecting all the instruments to the same power circuit, we found it helpful to isolate the chassis ground from Earth ground.
- Thermoelectric voltage noise caused by uneven airflow from ambient room air turbulence. As an example, let's consider a discrete voltage reference such as Linear Technologies LT1021. The datasheet shows output voltage noise versus time before and after a simple foam cup shield is removed. The results showed a strong influence from the airflow in the 0.01 Hz to 1 Hz band.⁵

E4727A Noise Measurement Solution

Fortunately, the E4727A Advanced Low-Frequency Noise Analyzer (A-LFNA) architecture helps address each of the noise measurement challenges presented above. To measure noise in a CMOS device, a source measurement unit like the Keysight B1500A is used to apply bias and measure DC operating points. When measuring noise however, the source measurement unit (SMU) noise contribution must be filtered out. The voltage noise is amplified and analyzed using a high-speed digitizer. Figure 12 presents one possible configuration of noise measurement, although many others are possible using these modules. The variable resistance, switching and filtering functions are included in the A-LFNA modules, which when combined with the A-LFNA software, leads to a powerful and accurate noise measurement solution.

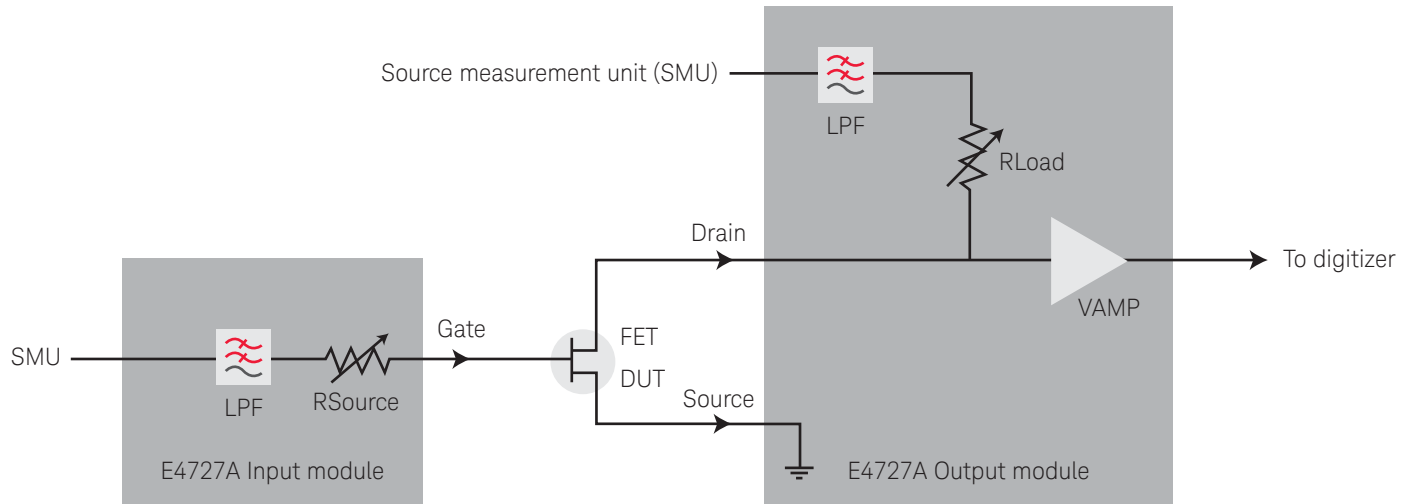


Figure 12. Drain voltage noise amplified and digitized, while maintaining control of source and load impedances and avoiding corruption of the noise data from the source measurement unit bias.

For different types of devices, different source and load impedances (R_{Source} and R_{Load}) are required. For example, if R_{Load} is too low, the poor noise voltage transfer to the digitizer will degrade signal-to-noise ratio and measurement sensitivity. If R_{Load} is too high, then the thermal noise of the resistance will dominate the noise measurement, also reducing measurement sensitivity. Excessive R_{Load} will furthermore play against the input capacitance of the amplifier "VAMP" to roll off the apparent noise measurement. The A-LFNA software is able to judiciously select R_{Source} and R_{Load} based on device type (FET, diode, BJT, etc.) and device current, which in turn has a strong impact on the impedances presented by the device. Given its selection, the software can predict the frequency at which the data has rolled off due to the RC filtering from the amplifier and chop the data at that frequency. Figure 13 illustrates measured data on an NMOS device at a number of bias currents. In this case, since the input impedance of the MOSFET is exceedingly high, $R_{Source} = 0 \Omega$. We observe evidence of varying R_{Load} at different current levels based on the cutoff frequency of the measurement. An ultra-low frequency amplifier ("VAMP-ULF") is switched in for measurements below 1 Hz.

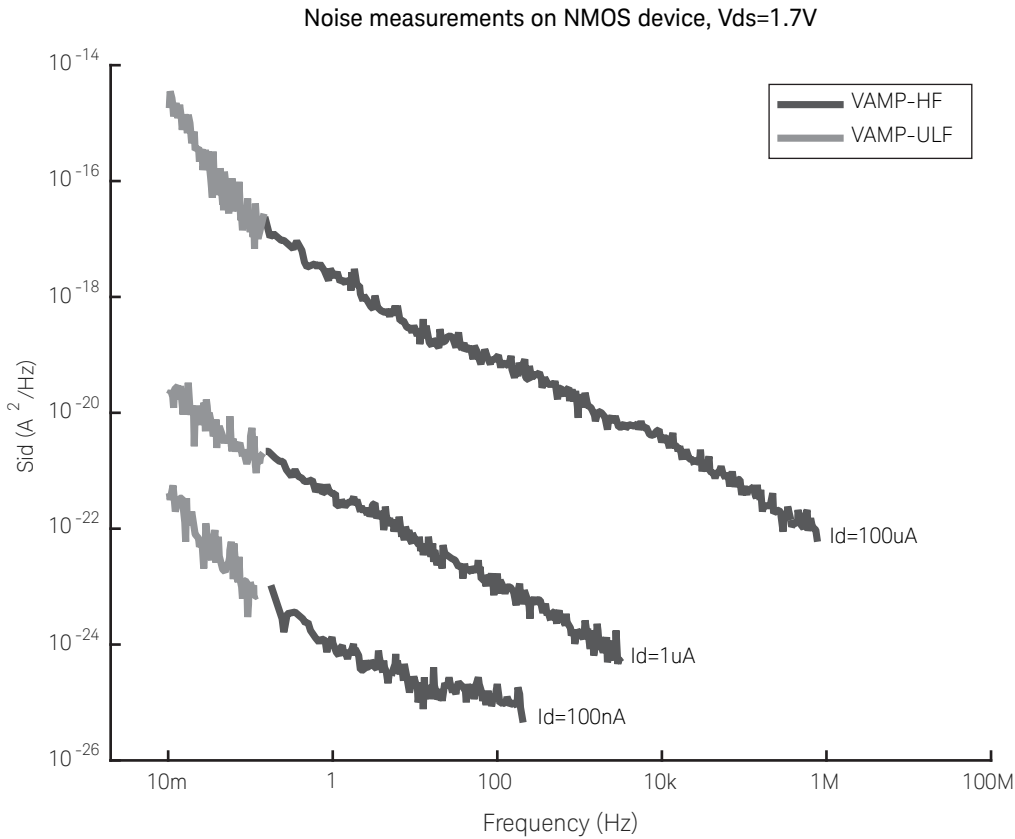


Figure 13. Noise data measured on a typical NMOS transistor at drain current levels of 100 μA , 1 μA and 100 nA.

Best Solution for Device 1/f Noise Measurement

The E4727A hardware consists of a series of modules paired with a PXI chassis housing a mainframe computer and digitizer. These modules are connected to a source measurement unit like the B1500A to enable both flexible and clean device biasing and noise signal conditioning, as shown in Figure 14.

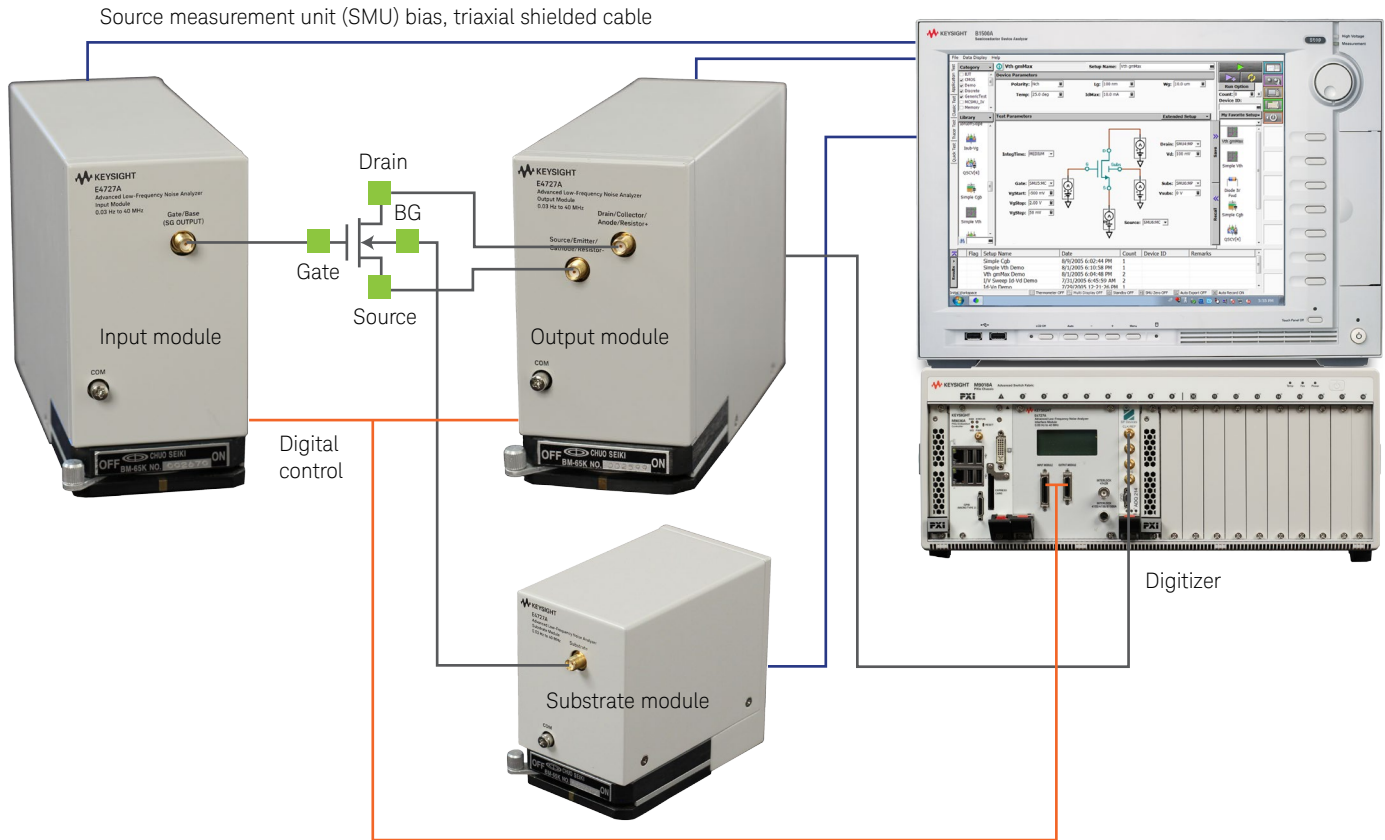


Figure 14. E4727A is combined with a source measurement unit like the B1500A to create a powerful noise modeling platform.

Due to their small size, the modules may be positioned as close as possible to the device under test, so as to minimize the undesired parasitic capacitance from the cabling. Figure 14 illustrates how the output module may be connected across the drain and source of an FET. It may be similarly connected across the collector and emitter of a bipolar transistor, anode and cathode of a diode, the two terminals of a resistor or the output terminals of an operational amplifier IC. A “fixture module,” included with the E4727A and shown to the top right in Figure 15, facilitates measurements on discrete packaged components. On-wafer testing is controlled by an easy-to-use software interface that tracks device location, wafer lot and geometry. The resultant data may then be ported over to powerful device modeling software like Model Builder Program (MBP) and Integrated Circuit Characterization and Analysis Program (IC-CAP).



Figure 15. Modules of E4727A: interface module, input module, output module, substrate module and test fixture module.

Conclusion

The Keysight E4727A Advanced Low-Frequency Noise Analyzer is the next-generation system for characterization and analysis of 1/f flicker noise and random telegraph signal noise (RTN). Designed for on-wafer probed devices, discrete package devices, and low noise integrated circuits, it uniquely allows for versatile noise measurement under diverse conditions, including: ultra-low frequency, ultra-low current, high current, high voltage, or high power. Given its state-of-the-art noise sensitivity and modular design, the E4727A is well suited for low frequency device noise measurements, especially when paired with a source measurement unit like the B1500A. For device modeling, characterization and statistical process control, this solution features an easy-to-use software platform. Measurements ranging from 0.03 Hz to 40 MHz are now possible, enabling device and circuit designs that push the frontier in sensitivity and noise.

Items		Specifications
Measurement devices		FET, BJT, Diode, Resistor, Circuit
Maximum frequency range		0.03 Hz ~ 40 MHz
AMP		Voltage AMP x3, Current AMP x2
Voltage AMP	Noise floor	-183 dBV ² /Hz (0.67 nV/√Hz)
	Corner frequency	20 Hz
Current AMP	Noise floor	1E-23 A ² /Hz
	Corner frequency	200 Hz
Maximum bias range		200 V/0.1 A (10 Wmax)

Table 2. Key specifications for E4727A Advanced Low-Frequency Noise Analysis system.

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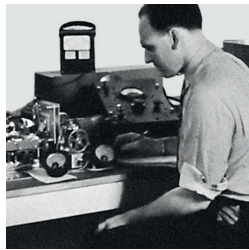
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