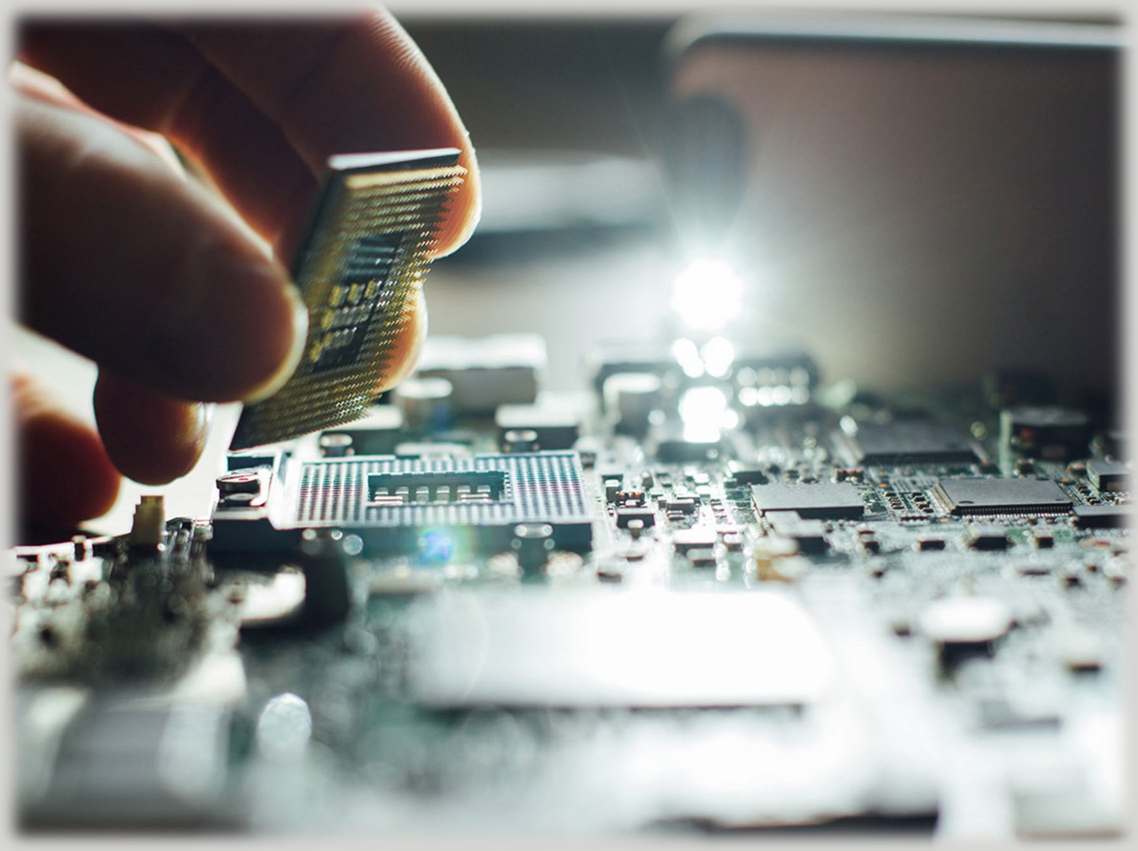
PRODUCT BROCHURE



Semiconductor/IC Design and Test in Research and Teaching

KEYSIGHT

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Introduction

In the intricate and rapidly evolving realm of Integrated Circuits (ICs), the convergence of innovation and reliability stands as a critical imperative. Ensuring the seamless operation, performance, and longevity of these microelectronic marvels requires a multi-faceted approach. This is where IC test and measurement, coupled with sophisticated design simulation, emerge as indispensable cornerstones of the semiconductor industry. In this landscape, Keysight Technologies shines as a trailblazer, offering comprehensive solutions that shape the trajectory of IC development, from inception to realization.

In this brochure, we delve into the symbiotic importance of IC test and measurement, coupled with cutting-edge design simulation, in the world of integrated circuits. With a magnifying glass on the offerings of Keysight Technologies, we aim to underscore how these tools intertwine to support the entire IC lifecycle – from concept and design validation to manufacturing and quality assurance. By understanding the synergies between meticulous testing and virtual design exploration, we uncover how Keysight continues to be an architect of innovation, steering the course of IC evolution in an increasingly interconnected world.

Purpose of This Brochure

This brochure provides suggestions from simulation to validation and experiments to help educators set up a semiconductor/IC teaching lab.

- The first section introduces and summarizes IC related solutions including IC design/simulation, parametric test, and digital/analog/mixed signal IC test.
- The second section provides turnkey semiconductor teaching solutions from basic to advanced.
- The third and fourth sections introduce practical teaching experiment examples for RFIC and power electronics.
- The final section presents the Digital Learning Suite (DLS), which is designed to make teaching and learning efficient and enabling automated test capability for teaching and research.

Semiconductor/IC Solution: An Overview

The Integrated Circuits (IC) design and testing life cycle is a complex process that involves precision and expertise to meet the required specifications. During the cycle, there are iterations, optimizations, and validations to ensure the final IC meets the desired performance and reliability standards.

The IC life cycle begins with software modeling and simulation based on specifications and requirements for the IC. Then, the design is etched onto a photomask and transferred onto the silicon wafer during the wafer foundry stage. After wafer testing, the components are packaged and undergo functional testing to ensure they are functioning correctly.

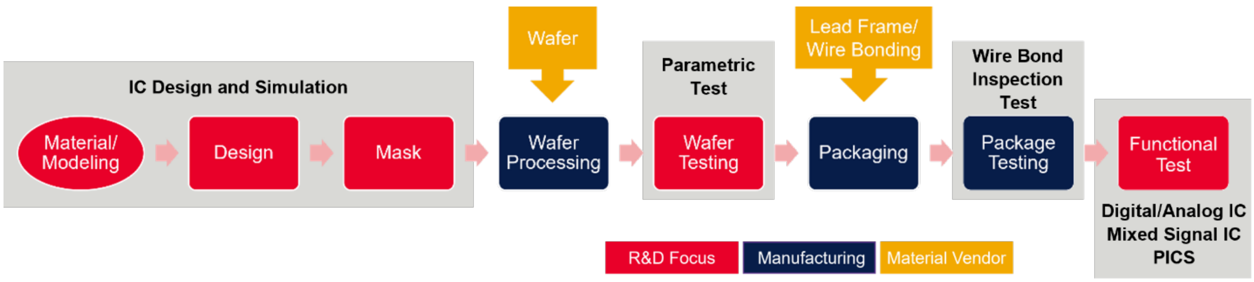


Figure 1. IC Design and testing life cycle

Challenges in IC design and testing:

- Miniaturization, hybrid integration of electro/optical technology increases design complexity, thus test coverage and methodology.
- Power consumption, especially in portable devices. While lower power consumption is desirable for longer battery life, this can be difficult to achieve considering high-performance requirement in terms of data rate.
- The pressure to bring products to market quickly can be a challenge for IC designers. Shorter product cycles mean that work must be done quickly, which can lead to mistakes and oversights.

To address these challenges, Keysight can help in every stage to accelerate the success of customers by providing not only powerful software, but also hardware and customized services.

IC Design and Simulation

Every year, designers push new limits: longer battery life, smaller components, higher levels of integration, and hours of setting up and running simulations. As engineers work to create workarounds to connect multiple design tools, there are mountains of data waiting to be measured and analyzed. Meanwhile, wireless standards are evolving quickly, which means keeping up with the strong demands of modern technology requires a whole new approach.

Keysight's PathWave Design software is a suite of electronic design automation software tools that accelerate product development by reducing the time engineers spend in the design and simulation phases. Its libraries and customized simulators shorten setup time. The software also reduces time spent in importing and exporting designs and fixing errors associated with changing tools as it seamlessly integrates circuit design, Electromagnetic (EM) simulation, layout capabilities, and system level modeling.

PathWave Device Modeling (IC-CAP)

PathWave Device Modeling (IC-CAP) software is the industry standard for DC and RF semiconductor device modeling. The Integrated Circuit Characterization and Analysis Program (IC-CAP) extracts accurate compact models used in high-speed/digital, analog and power RF applications. Today's most advanced semiconductor foundries and IDMs rely on IC-CAP for modeling silicon CMOS, Bipolar, compound Gallium Arsenide (GaAs), Gallium Nitride (GaN), and many other IC device technologies. IC-CAP is the most advanced, customizable modeling software and includes measurement, simulation, optimization, and statistical analysis tools.

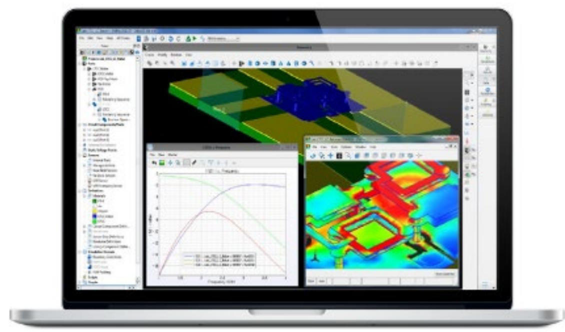
- Open modeling software architecture enables maximum accuracy and provides ultimate flexibility to create and automate measurement, extraction and verification procedures.
- Turnkey extraction solutions for industry standard CMOS models, such as BSIM3/BSIM4, PSP, and HiSIM, minimize the learning curve and maximize model accuracy.
- Most direct links to commercial simulators ensure consistency between extracted models and the simulators used by circuit designers.

PathWave Advanced Design System (ADS)

Modern RF and microwave designs require multi-chip modules with more elaborate interconnects and packaging. As complexity in electronic design increases and with 5G requiring higher frequencies and broader modulation bandwidth, there is more simulation and measurement data to analyze than ever before. Despite these time-consuming challenges, designers are often pressured to accelerate their time-to-market to stay ahead of the competition. Performing circuit analysis on multiple devices can be time consuming and difficult.

PathWave Advanced Design System (ADS) is Keysight's leading RF, microwave, signal integrity, and power integrity design platform. With multiple libraries, bundles, design guides, and simulation elements, PathWave ADS is the one software tool to help you overcome any design challenge. PathWave ADS provides a complete, integrated set of easy-to-use 3D EM circuit and system simulators, allowing you to perform EM and circuit co-simulation in one single tool. PathWave ADS combines schematic, layout, circuit, electro-thermal co-simulation, and three full-wave 3D EM technologies with Integrated Circuit (IC), package, laminate, PCB, and 3D EM component co-design in one software tool to dramatically improve productivity and reduce cost.

PathWave EM Design (EMPro)



PathWave EM Design (EMPro) is an EM simulation design platform for analyzing the 3D EM effects of components such as high-speed and RF IC packages, bond wires, antennas, on-chip and off-chip embedded passives, and PCB interconnects. RF board designs include 3D components and connectors that need to be characterized to high frequencies. Component and connector designs created in other CAD tools can be imported into PathWave EM Design (EMPro). They can then be simulated using either Finite Element Method (FEM) or Finite Difference Time Domain (FDTD) simulation technology. High-frequency components are sensitive to interactions with surrounding PCB traces and vias. These 3D components can be created and simulated in PathWave EM Design (EMPro), and then combined with a board layout in PathWave ADS for complete 3D EM simulation using FEM technology.

PathWave RF Synthesis (Genesys)

PathWave RF Synthesis (Genesys) is an affordable, accurate, easy-to-use RF and microwave circuit synthesis and simulation tool created for the circuit board and subsystem designer. Automatic circuit synthesis of matching networks, filters, oscillators, mixers, transmission lines, PLL, and signal routing structures enable engineers without prior expertise to design these components quickly.

PathWave RFIC Design (GoldenGate)

PathWave RFIC Design (GoldenGate) is an advanced simulation and analysis solution for integrated mixed signal RFIC designs that is fully integrated into the Cadence Analog Design Environment (ADE). It provides the framework for RFIC designers to rapidly simulate circuits, verify specifications, and validate potential yield of complex highly integrated devices. You can analyze circuit manufacturability using industry standard techniques such as Monte Carlo, as well as unique Keysight statistical mismatch and process analyses.

PathWave Model Builder

PathWave Model Builder is a complete silicon turnkey device modeling software. It integrates device simulation, model parameter extraction, and optimization. PathWave Model Builder supports all popular compact models including the latest BSIM-CMG, BSIM-IMG, and BSIM6 for DC, AC, and RF applications. The open interface enables optimization flow customization, device target definition, and the ability to define GUI operations.

PathWave Model QA

SPICE model validation is a critical step in the device modeling design flow, but difficult to conduct automatically. PathWave Model QA is the industry standard SPICE model signoff and acceptance software. You can easily use it to identify model issues with customizable knowledge-based checking routines. PathWave Model QA performs comparison and documentation automatically, while ensuring design success using advanced process technologies.

PathWave WaferPro

PathWave WaferPro software performs automated wafer-level measurements of semiconductor devices such as transistors and circuit components. It provides turnkey drivers and test routines for a variety of instruments and wafer probers. Its new user interface makes it easy to set up and run complex wafer-level test plans, while the Python programming environment enables powerful customization capabilities.

For More Information

For further insights and resources, visit www.keysight.com/find/design-software.

IC Parametric Test

Constant advances in semiconductor device scale and integration are leading to rapid increases in the number of devices on a single semiconductor chip. Quick process flaw detection and improved yield for semiconductor chips are becoming more important than ever for semiconductor device manufacturers. As more evaluation items using various test structures are required in process integration and process monitoring, the parametric test plays a crucial role in evaluating those evaluation items.

IC parametric testing is a critical step in the manufacturing process of integrated circuits. It involves testing the individual electrical parameters of each IC chip to ensure that it meets the required performance specifications.

B1500A Semiconductor Device Analyzer

Keysight B1500A Semiconductor Device Parameter Analyzer of Precision Current-Voltage Analyzer Series is an all-in-one analyzer supporting IV, CV, pulse/dynamic IV and more, which is designed for all round characterization from basic to cutting-edge applications. It provides a wide range of measurement capabilities to cover the electrical characterization and evaluation of devices, materials, semiconductors, active/passive components, or virtually any other type of electronic device with uncompromised measurement reliability and efficiency. In addition, the modular architecture of the B1500A with ten available slots allows you to add or upgrade measurement modules if your measurement needs change over time.

Key Features	Benefits
Precision voltage and current measurement (0.5 μV and 0.1 fA resolution)	• Accurate characterization of low-level voltages and currents.
Accurate and low-cost solutions to switch between multi-frequency (1 kHz to 5 MHz) capacitance measurement (CV, C-f, and C-t) and current/voltage (IV) measurement.	• Switch between CV and IV measurements without the need to re-cable. • Maintain low-current measurement resolution (down to 1 fA with SCUU and 0.1 fA with ASUs). • Full CV compensation out to the DUT.
Ultra-fast IV measurements with 100 ns pulsing and 5 ns sampling rate	• Capture ultra-fast transient phenomena not accurately measurable with conventional test instruments.
Over 300 ready-to-use application tests	• Reduce the time needed to learn the instrument, make a measurement, and become productive.
Curve tracer mode with oscilloscope view	• Develop tests interactively and immediately view the device characteristics. • Verify current and voltage pulses without any additional equipment (Oscilloscope view with MCSMU).
Powerful data analysis and robust data management	• Analyze measured data automatically without an external PC. • Store measured data and test conditions automatically and quickly recall this information at a later time.

4080 Series/P9002A Parametric Tester

Keysight 4080 Series offers a wide range of measurement capabilities required for fundamental parametric test. You can easily perform DC and capacitance measurements. 4080 Series supports three types of SMU for DC measurement. Several other instruments options, such as a Digital Voltmeter (DVM), a spectrum analyzer, and an LCR meter, provide enhanced measurement capabilities.

All parametric test designers want to improve the throughput and minimize any production downtime for the better cost of test in semiconductor wafer productions. To overcome some typical but difficult process test challenges in your semiconductor wafer production, Keysight offers the total solution on parametric test not only with hardware and software but with professional AE and CE consulting service.

B1505/6A Power Device Analyzer

Power devices play an important role in the modern world. They are used in a wide variety of applications from home electronics to industrial equipment, including familiar items like TVs, refrigerators, PCs, FAXs, air conditioners, industrial robots, and electric vehicles. Stricter energy efficiency requirements are driving not only changes in electrical and electronics circuit design but also improvements to power devices such as power MOSFETs and IGBTs. Specifically, it is desirable for power transistors to have lower power loss in their on-state and to possess a higher breakdown voltage in their off-state.

The B1505A Power Device Analyzer/Curve Tracer is a single box solution for power device evaluation from sub-pA to 10 kV and 1500 A, and precise measurement capabilities with 10 μs pulse and μΩon-resistance measurements.

- All-in-one solution for power device characterization up to 1500 A and 10 kV.
- Medium current measurement with high voltage bias (e.g. 500 mA at 1200 V).
- μΩ on-resistance measurement capability.
- Accurate, sub-picoamp level current measurement at high voltage bias.
- Fully automated thermal testing from -50 °C to +250 °C.

The B1506A Power Device Analyzer/Curve Tracer for Circuit Design is a complete solution that can help power electronic circuit designers maximize the value of their power electronics products by enabling them to select the correct power devices for their applications. It can evaluate all relevant device parameters under a wide range of operating conditions, including IV parameters such as breakdown voltage and on-resistance, as well as three terminal FET capacitances, gate charge, and power loss. The B1506A Power Device Analyzer/Curve Tracer for Circuit Design meets and exceeds all curve tracer capabilities with the following:

– A wide operation range of up to 3 kV/1500 A.
– Fully automated fast thermal test from -50 °C to +250 °C.
– Automatic power device (semiconductor and component) data sheet creation.
– Auto record function to prevent data loss.

PD1500A/1550A Double Pulse Test Solution

To enable consistent, reliable characterization of WBG semiconductors, Keysight created the PD1500A dynamic power device analyzer platform. Initially employing the Double Pulse Test (DPT) technique, it is developed in close collaboration with semiconductor manufacturers and designers from the energy and Electric Vehicle (EV) industries.

PD1500A delivers reliable, repeatable measurements of wide-bandgap semiconductors. The platform ensures user safety and protection of the system's measurement hardware. Other features include:

– Characterize 650 V, 1.2 kV, and 1.7 kV-rated power modules.
– ID/IC up to 200 A.
– Fast slew rates, high bandwidth measurement probes.

PD1550A Double Pulse Tester delivers reliable measurement of wide-bandgap power modules and eliminates the need to build, test, certify, and maintain an in-house system:

– VDS/VCE up to 1360 V, ID/IC up to 1000 A.
– Characterize 650 V, 1.2 kV, and 1.7 kV-rated power modules.
– Accurate VGS high-side characteristics using True Pulse Isolated Probe Technology.
– Accurate high current measurement with high-bandwidth RF compensation.
– Fast slew rates, high bandwidth measurement probes.
– Interface board with solderless contact and exchangeable gate resistor technologies.

E4727B Advanced Low-Frequency Noise Analyzer

The Keysight E4727B/W7802B is a turn-key solution to measure flicker (1/f) noise and RTN (Random Telegraph Noise) of a semiconductor's device. The Keysight W7801B is bundle software to control Keysight B1530A (WGFMU). These solutions can manage semi-auto probe stations and get mass wafer mapping noise data automatically.

The E4727B hardware is designed for both on-wafer and discrete device/circuit measurements and consists of a module paired with a PXIe computer and digitizer. The module is connected to a DC Source Measurement Unit (SMU) such as the B1500A to enable both flexible and clean device biasing and noise signal conditioning. An SMU is used to apply bias and measure DC operating points. However, when measuring noise, the noise contribution must be filtered out. The voltage noise taken from the device output is amplified and analyzed using high-speed digitization with customized FPGA. One possible configuration of noise measurement is shown below, although many others are possible. The variable resistance, switching, and filtering functions are included in the A-LFNA module.

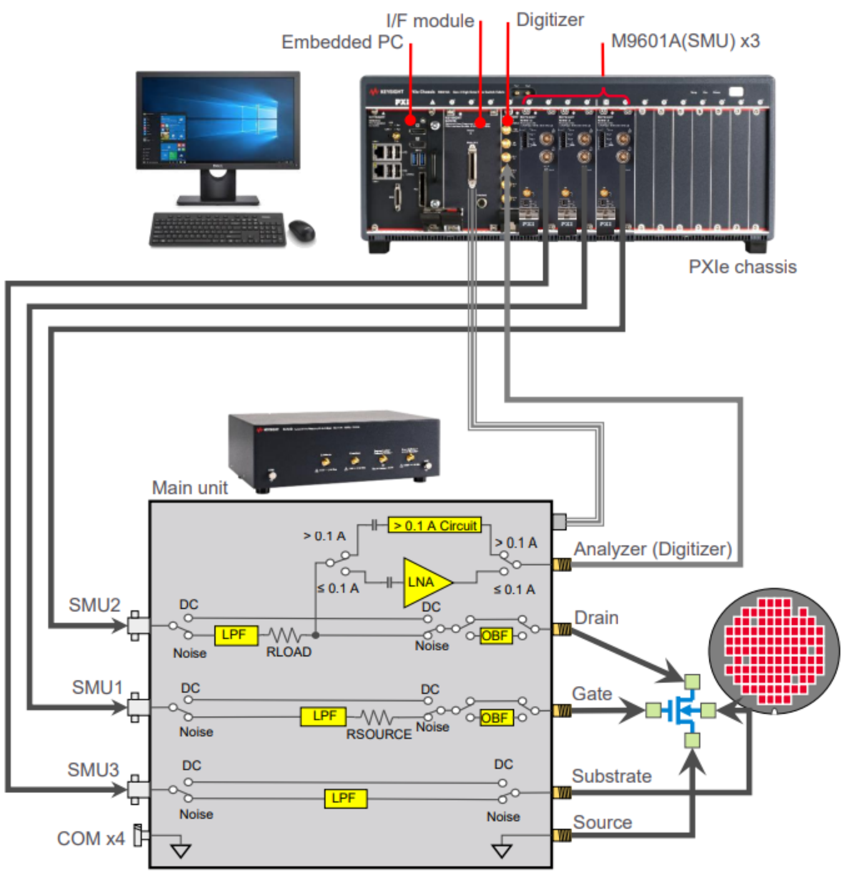


Figure 2. Simplified block diagram of E4727B system, which indicates LNA, LPF, and OBF (Oscillation Block Filter)

Different device types require different source and load impedance terminations. The E4727B is the only analyzer in the industry to offer 23 impedance values ranging from 0 ohms to 100 MΩ. The A-LFNA software can judiciously select RSOURCE and RLOAD based on device type (FET, BJT, Diode, Resistor, etc.) and measure DC characteristics.

Measurement capabilities:

– DC measurement
– Flicker (1/f) noise measurement
– RTN measurement
– Over 0.1A bias noise measurement

For More Information

For further insights and resources, check the following links:

www.keysight.com/us/en/products/parametric-test-solutions.html

www.keysight.com/us/en/product/B1500A/semiconductor-device-parameter-analyzer-system-mainframe.html

www.keysight.com.cn/cn/zh/assets/3120-1435/data-sheets/E4727B-Advanced-Low-Frequency-Noise-Analyzer.pdf

Wire Bond Inspection Test

The Keysight electrical structural tester is a capacitive-based testing solution designed to identify wire bond defects accurately. Leveraging the advanced Part Average Test (PAT) analysis, the tester establishes a baseline from known-good units to swiftly detect deviations like near-shorts, stray wires, wire sweeps, and sags within Integrated Circuits (ICs). This capability ensures robust product quality management and significantly enhances manufacturing efficiency. The electrical structural tester enables you to:

- Test single-die wire bonded packages in singulated or strip-based form factor.
- Achieve high-volume production with up to 20 parallel test sites, achieving up to 72,000 IC Units Per Hour (UPH).
- Enhance yield through advanced methods like Marginal Retry Test (MaRT), Dynamic Part Averaging Test (DPAT), and Real-Time Part Averaging test (RPAT).

Figure 3. Simplified block diagram of E4727B system, which indicates LNA, LPF, and OBF (Oscillation Block Filter)

For More Information

For further insights and resources, check the following links:

https://www.keysight.com/us/en/product/Q3800A/electrical-structural-tester.html

https:/www.keysight.com/us/en/assets/3124-1580/videos/Keysight-Electrical-Structural-Tester.mp4

Digital IC and Analog IC Test

Digital ICs are designed to process digital signals, which are represented by binary values (0 and 1). They are used in a wide range of applications, including computers, mobile devices, and consumer electronics.

Analog ICs are designed to process analog signals, which are continuous signals that can take on any value within a range. They are used in a wide range of applications, including audio and video equipment, sensor interfaces, and power management.

Testing digital and analog ICs poses different challenges due to the nature of the signals they process.

- Digital ICs, which are designed for high-speed signals, require a high degree of accuracy and precision in their testing, along with specialized test equipment that can handle the high frequencies and ensure accurate data transmission. Digital ICs can also be complex, with many integrated functions and modes of operation. Testing such ICs requires a thorough understanding of the design and functionality, as well as specialized test equipment to ensure all functions are tested. What's more, Digital ICs process large amounts of data, and testing such ICs requires the generation and transmission of large volumes of test data. This can be time-consuming and require specialized test equipment to handle the volume of data.
- Testing Analog ICs requires specialized equipment that can handle the noise and distortion inherent in analog signals, as analog signals are continuous and can be affected by noise and distortion, which in turn impacts the accuracy of the test results. Since analog signals have a wide range of amplitudes, it is a challenge to test the performance of the IC across the full range of amplitudes. It requires specialized equipment that can handle the range of signal amplitudes and ensure accurate testing. Analog ICs can also be sensitive to temperature and other environmental factors, which can affect their performance. Testing such ICs requires specialized equipment that can control the temperature and other environmental factors to ensure accurate results.

High-Speed Digital Standards Compliance Test

Emerging technologies such as 5G, artificial intelligence, virtual reality, the Internet of Things (IoT), and autonomous vehicles generate an enormous amount of data in the network, creating new computing and performance demands in the data center. Each new generation of high-speed computing standards introduces new features and faster data transfer rates, creating fresh test challenges for digital designers. Because standards evolve quickly, Keysight's solutions test specific industry standards, reducing time and ensuring compliance and interoperability of devices. This section covers the following standards:

- **Peripheral Component Interconnect Express (PCI Express® or PCIe®)**

  PCIe is a core technology used in many types of computer servers and endpoint devices. The PCI Special Interest Group (PCI-SIG®) defines specifications and compliance tests that guarantee the interoperability of PCIe systems. Each generation of the PCIe standard doubled the data transfer rate and increased the complexity of test. The PCISIG approves test solutions to ensure that tested products comply with the standard.

- **Double Data Rate (DDR) memory**

  Each new generation of the DDR Synchronous Dynamic Random-Access Memory (SDRAM) standard delivers increased speeds, reduced footprint, and improved power efficiency. However, these improvements introduce design and test challenges for chip designers and device manufacturers. Test the performance of DDR devices to ensure that they meet the specifications defined by the Joint Electronic Devices Engineering Council (JEDEC).

- **Universal Serial Bus (USB)**

  The USB Type-C connection includes four sets of transmit and receive pairs, which enables one, two, or all four channels to transfer data simultaneously at any time. Enhanced power delivery provides up to 100 Watts (W) for bidirectional device charging. These combined Type-C features and enhancements significantly increase the complexity of USB Tx / Rx conformance testing. Automated compliance test software can quickly and accurately validate USB interfaces.

- **Mobile Industry Processor Interface (MIPI®)**

  The Mobile Industry Processor Interface (MIPI®) standard defines industry specifications for the design of mobile devices such as smartphones, tablets, laptops, and hybrid devices. MIPI interfaces play a strategic role in 5G mobile devices, connected car, and IoT solutions. The MIPI standard defines three unique Physical (PHY) layer specifications: MIPI D-PHY®, M-PHY®, and C-PHY®. MIPI D-PHY and C-PHY physical layers support camera and display applications, while the high-performance camera, memory, and chip-to-chip applications are supported on top of the M-PHY layer. We can help you test all key measurement parameters according to the MIPI standard and ensure the performance of your mobile devices.

Below is a solution summary for high-speed digital IC.

High-Speed Digital Signal Interface		Hardware	Software
MIPI	Tx	Infiniium V-Series Oscilloscopes	• D9050MPHC – MIPI M-PHY V5.0 Compliance Test Software • D9040MPHC – MIPI M-PHY Compliance Test Software • D9020DPHC – MIPI D-PHY Compliance Test Software • D9010CPHC – MIPI C-PHY Compliance Test Software
	Rx	M8020A J-BERT High-Performance BERTs M8195A 65 GSa/s Arbitrary Waveform Generator	• M8085A MIPI® Receiver Test Solution • N5990A Automated Compliance and Device Characterization Tests
	Impedance/ Return Loss Test	E5080B ENA Vector Network Analyzer	• MIPI M-PHY Hot TDR Test MOI using Enhanced TDR Software • MIPI C-PHY Hot TDR Test MOI using Enhanced TDR Software • MIPI D-PHY Hot TDR Test MOI using Enhanced TDR Software
USB	Tx	Infiniium UXR-Series	• D9040USBC USB4 Tx compliance test software • D9020USBC USB 3.2 Tx compliance test software • U7243C USB 3.1 transmitter compliance software

High-Speed Digital Signal Interface		Hardware	Software
	Rx	M8020A J-BERT high-performance BERT/ M8040A high-performance BERT Infiniium UXR-Series	• N5991U40A USB4 receiver compliance test SW • N5991U32A USB 3.2 receiver compliance test SW
PCIe	Tx	Infiniium UXR	• D9050PCIC PCI Express transmitter test compliance SW for PCI Express 5.0 • D9040PCIC PCI Express transmitter test compliance SW for PCI Express 4.0
	Rx	M8020A J-BERT high-performance BERT/M8040A high-performance BERT Infiniium UXR-Series	• N5991 receiver compliance test automation platform
DDR	Tx	Infiniium UXR	• D9050DDRC DDR5 Tx compliance test software • D9040DDRC DDR4 and LPDDR4 compliance test software • D9050LDDC LPDDR5 Tx compliance test software • D9030DDRC DDR3 and LPDDR3 compliance test software
	Rx	M8020A J-BERT high-performance BERT	• M80885RCA compliance software
	Protocol	U4164A Logic Analyzer Module	• B4661A memory analysis software

Low Power IC Characterization

As mobile devices get faster and sport more functions and features, they run up against battery limits. Technology developers must confront the trade-off between performance and power consumption and optimize accordingly. Developers also need to evaluate and verify device reliability to prevent potential defects before product release. If defects are not caught early and mitigated, costs can spiral out of control. It is a massive challenge to fix problems once a product has shipped. There are three challenges for mobile device designers:

– Realize high-speed operation at a lower voltage with the circuit design.

– Build advanced power management schemes for high-performance and low power consumption.

– Execute efficient evaluation, validation, and debugging.

As the table below shows, there is no good way to measure fast, low current AC waveform.

Instrument	Pro	Con
Shunt resistor and oscilloscope > 1 mA	• Wide bandwidth • Simple • Low cost	• Large voltage drop • High noise floor • Limited dynamic range
Current probe and oscilloscope > 1 mA	• Low cost • Simple • Very common method	• Degauss and adjustment • High noise floor • Limited dynamic range
DMM (Digital Multimeter) < 1 µA	• General instrument • Low-level static current measurement capability	• No dynamic current measurement capability • No or poor GUI
N6705 (DC Power Analyzer) < 1µA	• Excellent solution for battery drain analysis • Source and measure	• Cannot use as standalone “meter” • Limited bandwidth (< 30 kHz)

The CX3300 Series is a solution that obtains detailed current profile measurements and performs analysis efficiently with one unit. It can capture the dynamic current of mobile devices from sleep mode to active mode in one measurement. Its five dedicated current/differential sensors yield a wide dynamic range, up to 16-bits resolution, and cover the current range of 150 pA to 100 A. Because of its low measurement noise, you can detect small signals that would be hidden by the measurement noise of other instruments. In the past, these small signals would not have been visible.

Key features:

– Wide bandwidth at 200 MHz.

– High-resolution/high-speed sampling at 14-bit (1 GSa/s)/16-bit (75 MSa/s).

– Low noise and a wide dynamic range with high sensitivity from sub-nA and sub-µV.

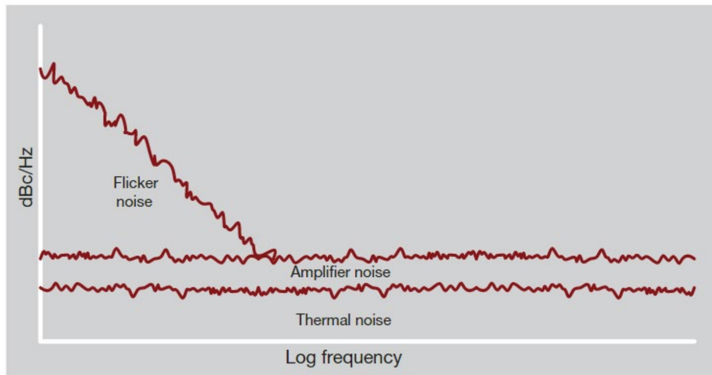
– Long-duration measurement capabilities up to 100 hours maximum.

– Waveform analytics, current profiler, and more efficient analysis functions on mainframe and PC.

VCO/PLL Phase Noise Measurement

Voltage-Controlled Oscillators (VCOs) and Phase-Locked Loops (PLLs) are two types of integrated circuits that play a crucial role in electronic systems. They are used to generate stable and accurate clock signals that are used to synchronize different components in the system.

VCOs and PLLs are essential components in electronic systems that require accurate and stable clock signals. They are used in a wide range of applications, from digital systems to analog systems. Accurate and stable clock signals are necessary for reliable operation of electronic systems and can affect the performance of the entire system.



Phase noise is a measure of the random fluctuations in the phase of an oscillator or clock signal and is an important parameter in the design and operation of Voltage-Controlled Oscillators (VCOs) and Phase-Locked Loops (PLLs). These fluctuations can be caused by a variety of factors, including thermal noise, flicker noise, and power supply noise. Phase noise is one of the most important figures of merit of a signal generating device and can well be a limiting factor in a mission-critical application in aerospace and defense, as well as in communications.

There are several ways to measure phase noise.

- **Direct-spectrum method**

  Direct-spectrum method to measure phase noise is simplest way. Limitations are related to shortcomings in the quality or performance of some spectrum analyzers: residual FM of the Local Oscillator (LO) of the analyzer, the noise sidebands or phase noise of the analyzer LO, and the analyzer noise floor can all affect the results. In addition, most spectrum analyzers measure only the scalar magnitude of the SUT noise sidebands. As a result, the analyzer is unable to differentiate between amplitude noise and phase noise. Finally, the process is complicated by the need for a noise measurement at every frequency offset of interest, and this is a very time-consuming task when performed manually.

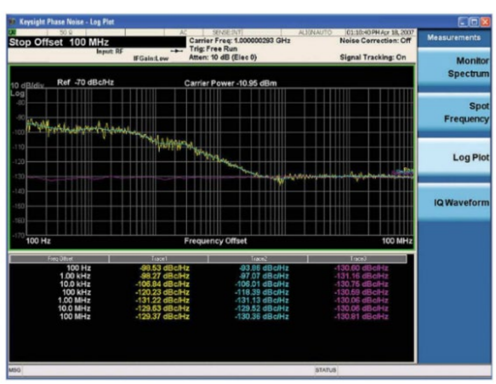


Figure 4. N9068A phase noise measurement application

- **Frequency-discriminator method**

  This method works best with free-running sources such as Inductor/Capacitor (LC) oscillators and cavity oscillators. These tend to produce noisy signals that have high-level, low-rate phase noise or high close-in spurious sideband conditions that can limit the performance of the PLL technique.

  One drawback of this method is a decrease in measurement sensitivity, especially at close-in offset frequencies. Longer delay line will provide improved sensitivity; however, it can reduce the signal-to-noise ratio and limit the maximum measurable offset frequency. In addition, the insertion loss of the delay line may be too great for the SUT output level to overcome.

Figure 5. N5511A phase noise test system

- **Two-channel cross-correlation method**

  This method uses two duplicate reference-source/PLL channels and calculates the cross-correlation between the two resulting outputs. Because any SUT noise present in both channels is coherent, it is not affected by the cross-correlation computation. In contrast, any internal noise generated by either channel is non-coherent and therefore diminished in the cross-correlation operation by the square root of the number of correlations. The number of correlation operations is a key factor in total measurement time.

Figure 6. E5052B Signal Source Analyzer (SSA)/E5055A SSA-X Signal Source Analyzer

Since the two-channel technique reduces measurement noise, it provides superior measurement sensitivity and, because it relies on DSP capabilities, it enhances sensitivity without requiring exceptional performance in the measurement hardware. This method also provides greater dynamic range than the digital discriminator method described above.

With these benefits, the two-channel cross-correlation method is an especially good choice when characterizing free-running oscillators. As a general observation, it provides excellent phase noise performance when measuring many types of sources and oscillators.

Non-Volatile Memory Devices Characterization

The recent rise in demand for smartphone technology has increased the need for Non-Volatile Memory (NVM) devices and the IoT continues to expand the application area of NVM. Flash memory is currently the mainstream for the storage device, but extensive research is underway with the next generation of NVMs such as ReRAM, PRAM etc., looking at expanding applications for lower power storage, storage class memory and the replacement of conventional volatile memory through the improvement of speed, performance, power consumption, reliability, and cost.

- **Measurement challenges**

  Many of the new NVM memories are made up of two terminal devices, where the on and off states are controlled by the set/reset pulse, and the on/off state is read by the reading pulse. The figure below shows a typical voltage pulse waveform applied to the NVM device, and the set/reset pulse is typically less than 1 µs. The device impedance changes drastically during the set/reset pulse, and it varies according to the pulse parameters such as level, transient time, and width, in addition to the material and fabrication process. Therefore, it is important to be able to measure how the impedance changes during the set/reset pulse and to study the device mechanisms and improve its performance, reliability and fabrication process or find suitable alternative materials.

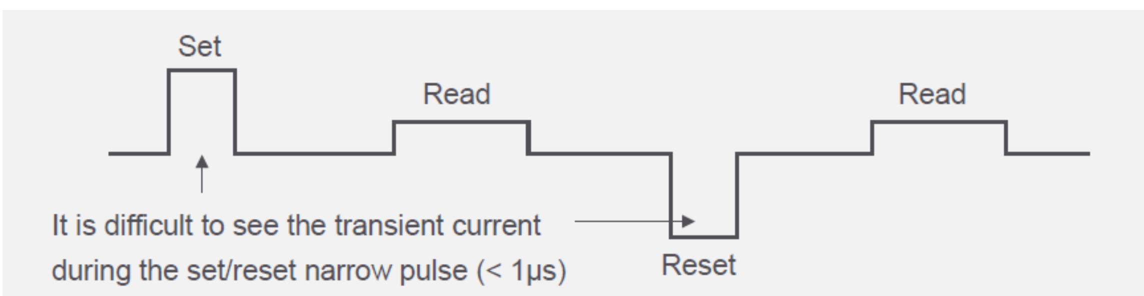


Figure 7. A typical pulse cycle for set-read-reset-read

Such high-speed measurements are too fast to record using a conventional SMU and an oscilloscope is commonly used instead. However, there are a number of challenges when using an oscilloscope:

- An oscilloscope cannot measure the current directly. To convert the current to voltage, an I/V converter (e.g. 50 Ω input resistance, external shunt resistance, I/V amp, etc.) must be used.
- Typical I/V converters limit the bandwidth for sensitivity or sensitivity for bandwidth. It is difficult for users to find or design appropriate I/V converters for their NVM devices.

– The dynamic range of current measurement can be limited, for example, when using 50 Ω input resistance or external shunt resistance for I/V conversion.

– The dynamic range and noise floor of the oscilloscope is not sufficient for low current measurement.

- **Solutions**

To understand the basic connections and check the CX3300 measurement performance, perform a simple pulsed IV measurement with a 100 kΩ discrete resistance, as shown in the following schematic.

The B1525A HV-SPGU of the B1500A semiconductor device parameter analyzer is used in this example, although any pulse generator can be used to apply the pulse. The pulse is applied to the DUT via 50 Ω feed-thru, which is needed to prevent reflection when the pulse is narrow.

Use the CX3300 with the CX1103A low side current sensor to measure the current. The CX1103A supports multiple ranges from 200 nA (100 kHz BW) to 20 mA (200 MHz BW), and the 200 μA range (9 MHz BW) is chosen in this example, from the viewpoint of current sensitivity and bandwidth trade-off.

In addition to the current measurement, the CX3300 supports the monitoring of the voltage using the CX1151A Passive Probe I/F Adapter (1 MΩ input) and allows you to compare the voltage and current at the same time. A tee connector is used to split the voltage to the DUT and the voltage monitor channel in the schematic.

You can also perform a synchronized measurement with the applied pulse. The CX3300 can be triggered just like an oscilloscope, and the measurement can be triggered by the current input, voltage input, or AUX trigger input. Triggering by the voltage monitor or AUX input may be useful unless the current condition is known.

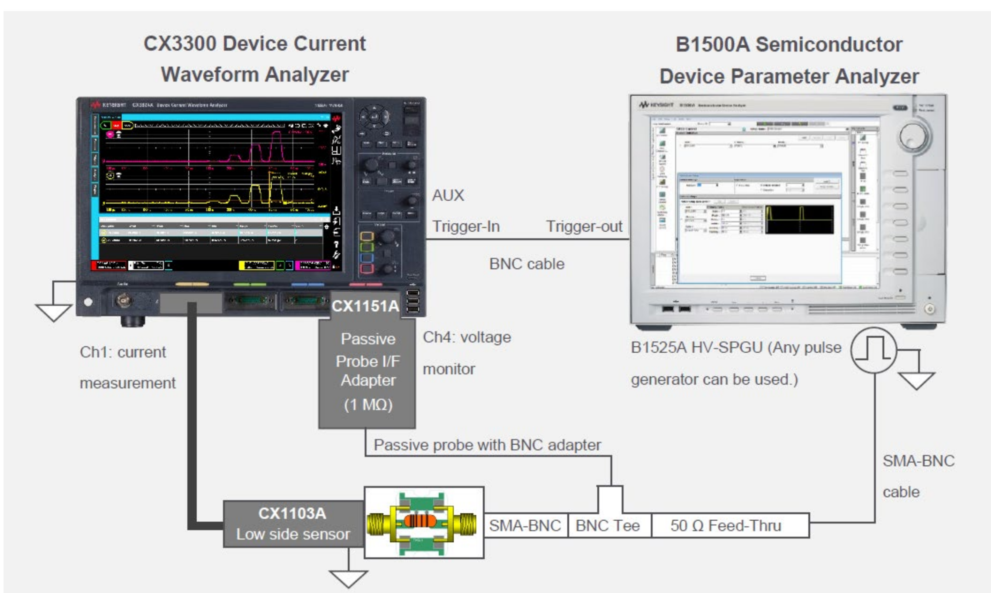


Figure 8. Setup example using a discrete device

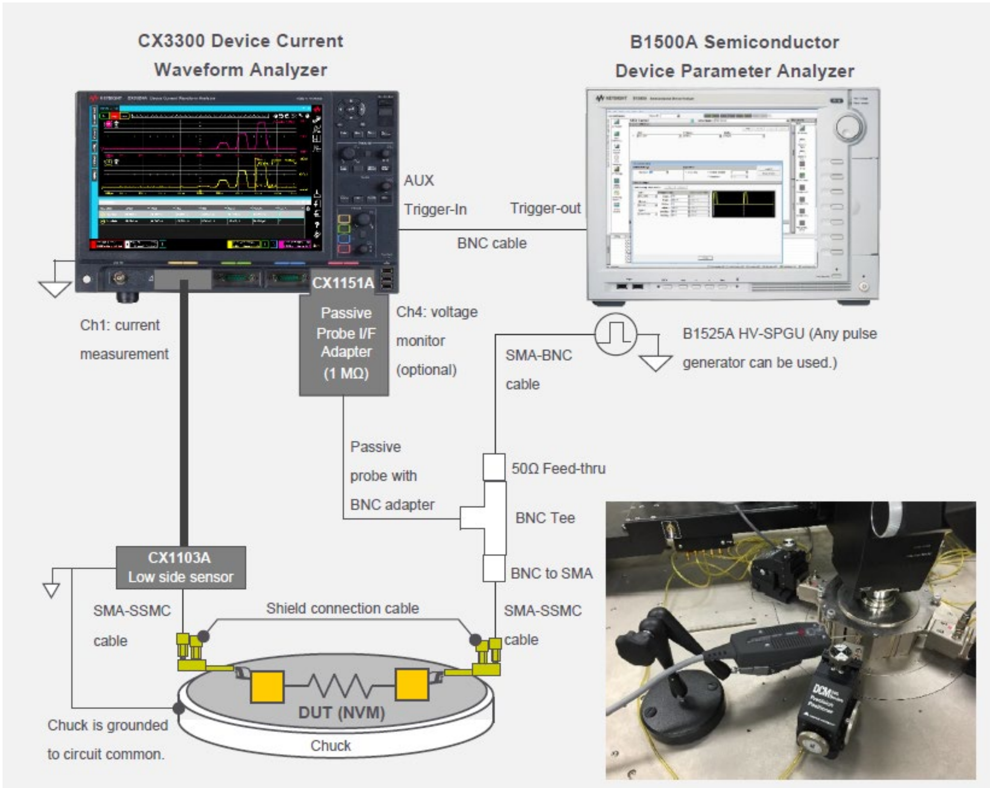


Figure 9. On-wafer measurement setup example

For More Information

For further insights and resources, check the following links:

www.keysight.com/us/en/solutions/high-speed-digital-system-design/mobile-industry-processor-interface-mipi.html

www.keysight.com/us/en/products/device-current-waveform-analyzers.html

www.keysight.com/us/en/product/E5055A/e5055a-ssa-x-signal-source-analyzer-1-mhz-to-8-ghz.html

https://www.keysight.com/us/en/assets/7018-05296/application-notes/5992-1631.pdf

Mixed Signal IC Test

Mixed-signal ICs are semiconductor devices that contain both analog and digital circuitry on the same chip. They are used in a wide range of applications, including telecommunications, consumer electronics, automotive, and industrial control systems.

The market trends for mixed-signal ICs include the increasing demand for integration of multiple functions on a single chip, as well as the growing need for low-power and high-performance devices. This has led to the development of advanced mixed-signal IC technologies, such as FinFET and FD-SOI, which offer better power efficiency and higher performance.

However, testing mixed-signal ICs can be challenging due to the complexity of the circuits and the need for accurate measurement of analog signals. Test challenges include ensuring signal integrity, accurate parameter extraction, and proper test coverage. To address these challenges, various test techniques and tools have been developed, such as mixed-signal test instruments and software, Built-In Self-Test (BIST) circuits, and system-level testing approaches.

ADC/DAC Test

ADC (Analog-to-Digital Converter) and DAC (Digital-to-Analog Converter) are two types of mixed-signal ICs that are widely used in various applications, including digital signal processing, communication systems, and audio and video processing.

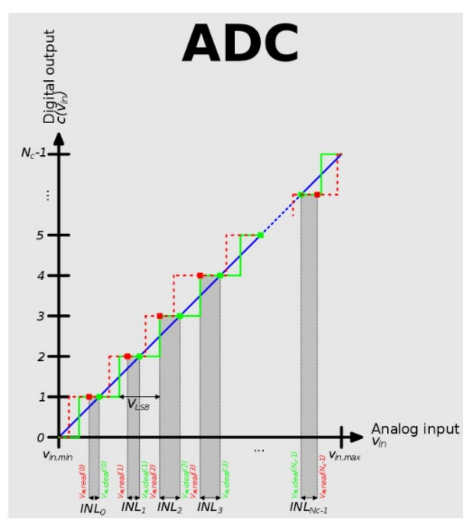
An ADC converts analog signals into digital signals, while a DAC converts digital signals into analog signals. The market trend for ADCs and DACs includes the increasing demand for higher performance, higher resolution, and lower power consumption. This has led to the development of advanced ADC and DAC technologies, such as successive approximation, delta-sigma, and pipeline architectures.

Testing ADCs and DACs can be challenging due to the need for accurate conversion and signal integrity, as well as the requirement for precise calibration and testing at different operating conditions. Test challenges include linearity, accuracy, timing, and noise, which can affect the performance of the devices. To address these challenges, various test techniques and tools have been developed, such as Built-In Self-Test (BIST) circuits, system-level testing approaches, and advanced test instruments and software.

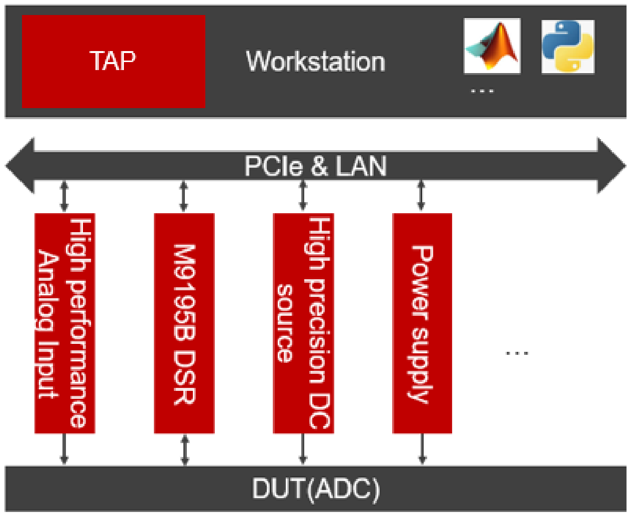
- **ADC automation test**

  For ADC test, there are two kinds of parameters to measure. First one is static parameters. INL/DNL are used to measure the linearity of ADC performance. For an ideal ADC, the output is divided into 2 power in uniform steps with the same width of input analog voltage.

  Any deviation from the ideal step width is the Differential Non-Linearity (DNL). DNL errors accumulate to produce a total Integral Non-Linearity (INL). It is defined as the maximum deviation from the ideal slope of the ADC and is measured from the center of the step. INL/DNL is a function of each ADC's particular architecture. It is not possible to remove its effects with calibration.



The other parameter is dynamic parameters such as SNR/SFDR/THD. However, those two kinds of parameters cannot be measured directly by instrument since we only got digital signal from ADC. Post-data processing is needed to calculate those parameters.



Create an ADC test solution by integrating Keysight hardware and software. Use the high-performance analog signal generator or U8903B audio analyzer as a dynamic test stimulus and the precision SMU as a static test stimulus. For the digital part, use the M9195B to receive the output of the ADC and send control signals to ADC to set its work state or register values. One M9195B has 16 channels and multi-board can be used for high resolution ADC test. The max sample rate of ADC that M9195B can support is 250 MHz. All instruments will work under Keysight TAP, a test automation platform, through PCIe or LAN.

Below are two reference test automation solutions for the ADC test:

– This reference test solution focuses on lower ADC sample rate and has the ability to control DUT by digital IO module.

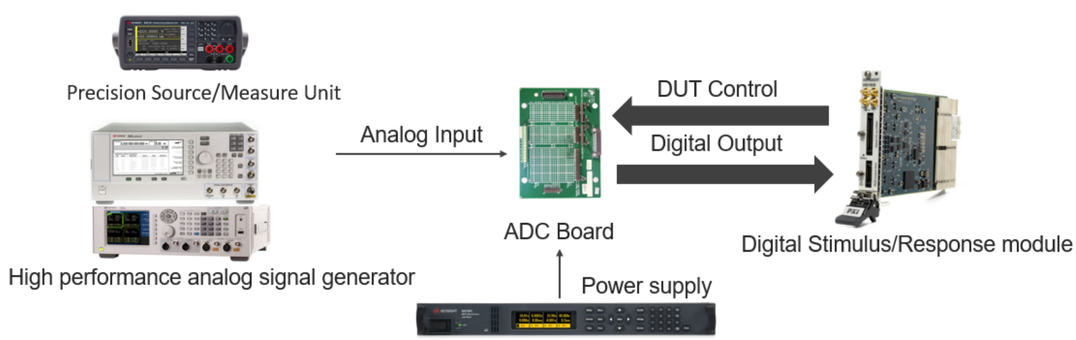


Figure 10. ADC automation test reference solution #1

– This reference test solution covers a higher ADC sample rate.

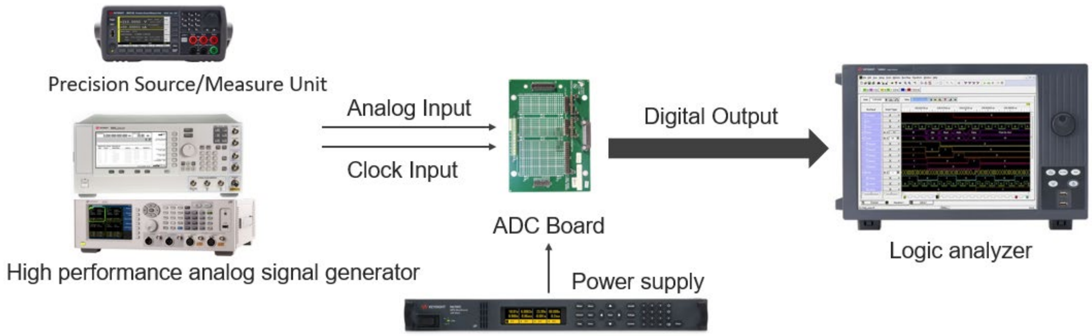
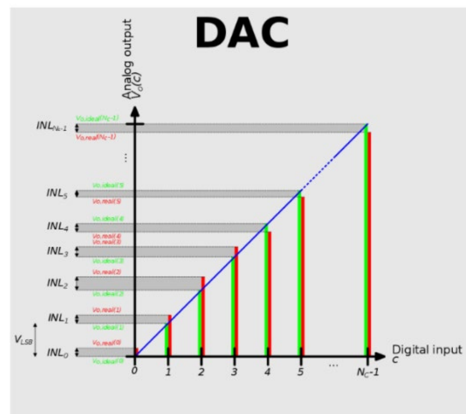


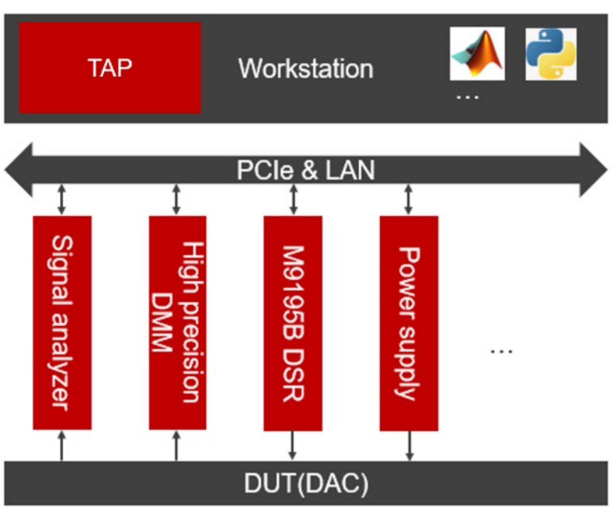
Figure 11. ADC automation test reference solution #2

- **DAC automation test**

  There are also two kinds of parameters to measure for a DAC test: static parameters and dynamic parameters. Dynamic parameters can be measured directly since the output of DAC is analog signal. Use a signal analyzer to measure the phase noise/THD/harmonics of the DAC.



  For static parameters, DNL/INL are also used to describe the linearity of the DAC. As mentioned before, for an ideal DAC, the output voltage is divided into 2 power in uniform steps with the same width of digital input. Any deviation from the ideal step width is the Differential Non-Linearity (DNL). INL is the integration of DNL. Using a DMM to receive output of the DAC will not provide the result directly as post data processing is required.



The DAC test solution includes the M9195B as the digital stimulus for the DAC and a signal analyzer or audio analyzer as the instrument for the dynamic parameter test. Use a high-precision DMM for the static parameter test as an analog signal receiver. Like the ADC test solution, all instruments are needed to create a solution. The digital pattern for the DAC must be generated according to different test types and states. TAP can help to automize the test sequence and integrate MATLAB/Python algorithm. For higher sample rate, AWG or FPGA might be suitable for the digital stimulus of the DAC.

The configuration can be different for different test requests. With Keysight, you not only get a single box instrument but also the right test solution for complex applications. Helped by the test automation engine, the test will be more automatic and flexible, and even compatible with a customized algorithm.

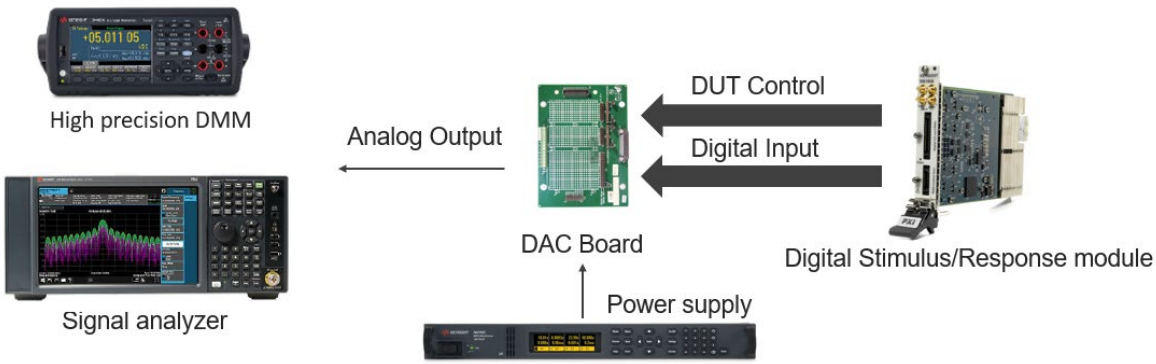


Figure 12. DAC automation test reference solution

NOTE: ADC/DAC test solutions are highly customized. Please contact Keysight for more information.

Power Amplifier Test

Power Amplifier (PA) is typically viewed as analog IC but nowadays, a PA is mostly considered as a mixed signal type. For example, the PA used in a mobile phone is not only just a PA as it also has passive components like switches and filters, as well as a digital control module. Envelope tracking and digital pre-distortion are the widely studied key technologies to improve the performance of the PA.

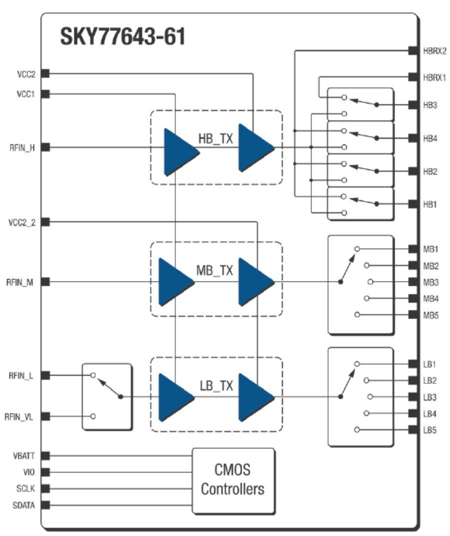


Figure 13. PA chip diagram from Skyworks Solutions, Inc. showing several bands and switches and an MIPI controller.

Testing the next generation RF PAs brings new challenges:

- Passive components integrated onto power amplifier duplex-type devices must be tested in addition to the PA.
- Envelope tracking and digital pre-distortion to overcome efficiency issues caused by high peak-to-average ratio modulation formats.
- Higher number of bands and modulation formats require additional test conditions.

- **Envelope Tracking (ET)**

  Envelop tracking is very useful to improve power efficiency as PA tends to consume a lot of power. However, in some cases, the PA does not need to be powered fully all the time since the signal is pulsed or in time division.

  As shown in Figure 14, the power level of the LTE uplink signal stays relatively low most of the time and goes to peak power only occasionally, but the PA is designed to deliver the highest efficiency only at peak power. Since the high power supplied to the PA will not be used most of the time, it is mostly dissipated as heat and causes battery drain, impacting the Thermal Design Power (TDP) of the mobile terminals. Envelope tracking has come to the forefront as a possible solution for this issue in mobile RF front end design. ET dynamically adjusts DC supply voltage based on the "envelope" of the PA input signal and delivers higher voltages only when needed, improving battery consumption and heat dissipation in the PA.

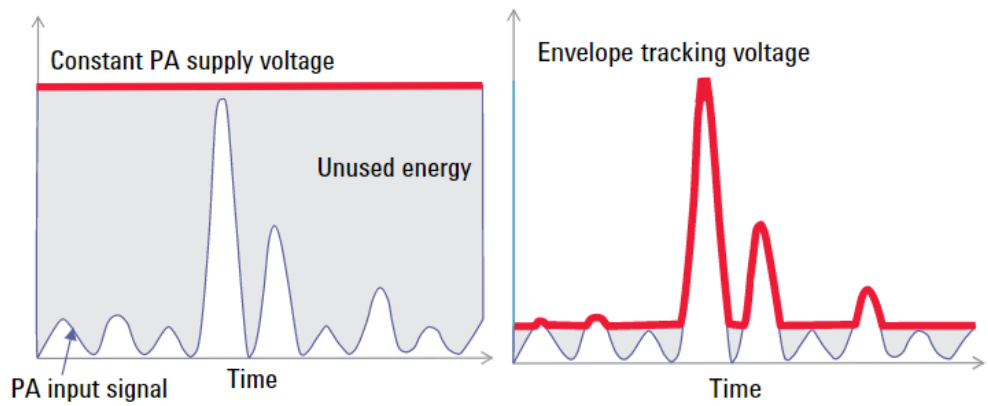


Figure 14. Time domain view of the input signal and bias

Here is the solution to test the PA with Envelope tracking, as shown in Figure 15.

Envelope Tracking Power Supply (ETPS) dynamically adjusts the power supply voltage to the PA. As defined in the MIPI™ standard, most ETPS have differential inputs and therefore, the envelope waveform generator must have differential output.

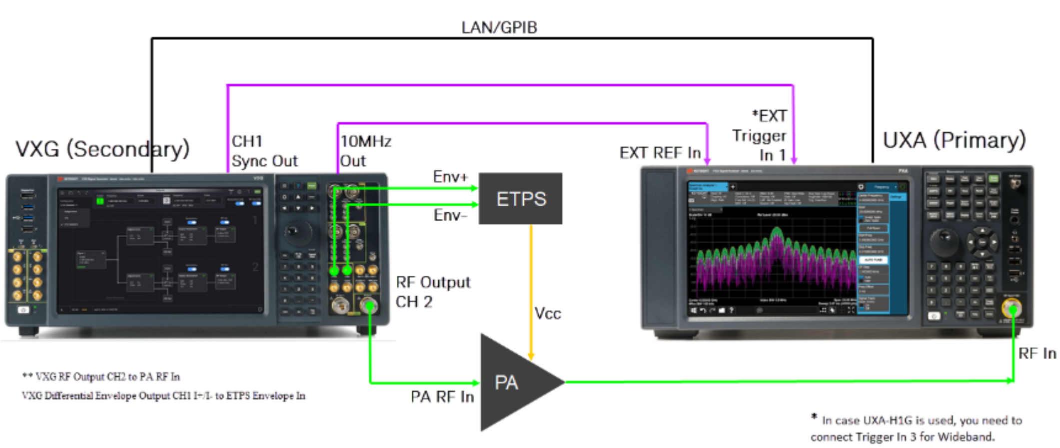


Figure 15. The instrument connection of Power Amplifier measurement with Envelope Tracking

Power supply voltage must be applied to the PA with precise timing relative to the input RF signal. Typically, the timing alignment between RF and envelope must be less than 1 ns. Rough timing adjustments between RF and envelope can be achieved with an oscilloscope before connecting to the ETPA and ETPS. However, due to internal delays in the ETPS and the RF PA, the final tuning must be done with the ETPA output using parameters such as EVM or ACLR.

- **Digital Pre-Distortion (DPD)**

  To reduce the nonlinearity, the power amplifier can be operated at a lower power (that is, *backed off*) so that it operates within the linear portion of its operating curve. However, newer transmission formats, such as Wideband Code Division Multiple Access (WCDMA) and Orthogonal Frequency Division Multiplexing (OFDM, 3GPP LTE), have high Peak-to-Average Power Ratios (PAPR); that is, large fluctuations in their signal envelopes. This means that the power amplifier needs to be backed off well below its maximum saturated output power to handle infrequent peaks, which result in very low efficiencies (typically less than 10%). With greater than 90% of the DC power being lost and turning into heat, the amplifier performance, reliability, and ongoing Operating Expenses (OPEX) are all degraded.

  This means power amplifiers with high Peak-to-Average Power Ratios (PAPR) signals can create non-linearity problems. When a high-power signal is applied to the PA input, the PA is not able to linearly amplify the signal, possibly resulting gain saturation and distortion, and ultimately leading to signal quality degradation, such as worse ACP and EVM.

  Digital pre-distortion technology can be used to compensate for the non-linear behavior of the PA. DPD applies *inverse* distortion to the PA input signal to cancel the distortion generated by the PA.

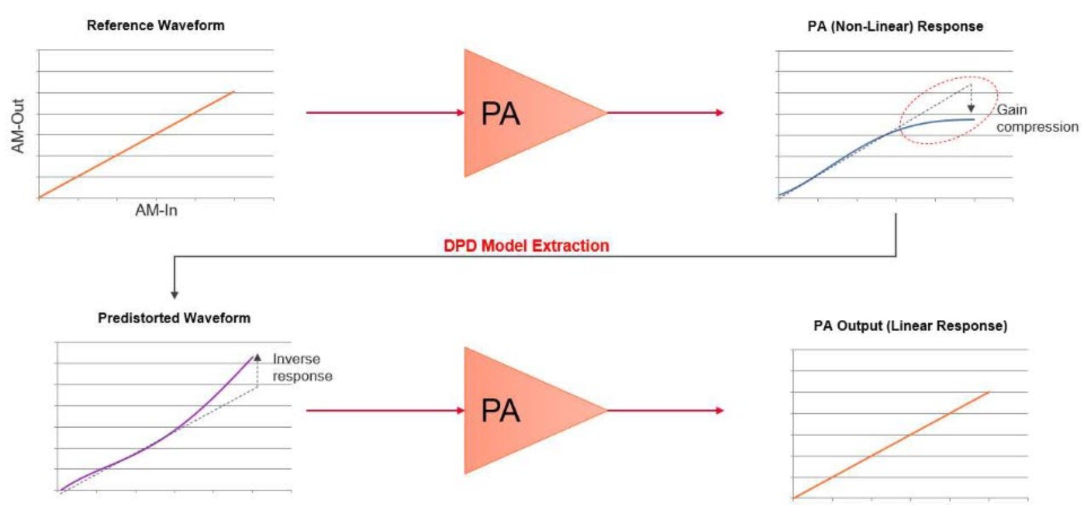


Figure 16. Digital pre-distortion

Below are two solutions to test the PA with DPD based on N9055EM0E power amplifier measurement application:

– This solution uses signal generator and signal analyzer with a power amplifier measurement application software.

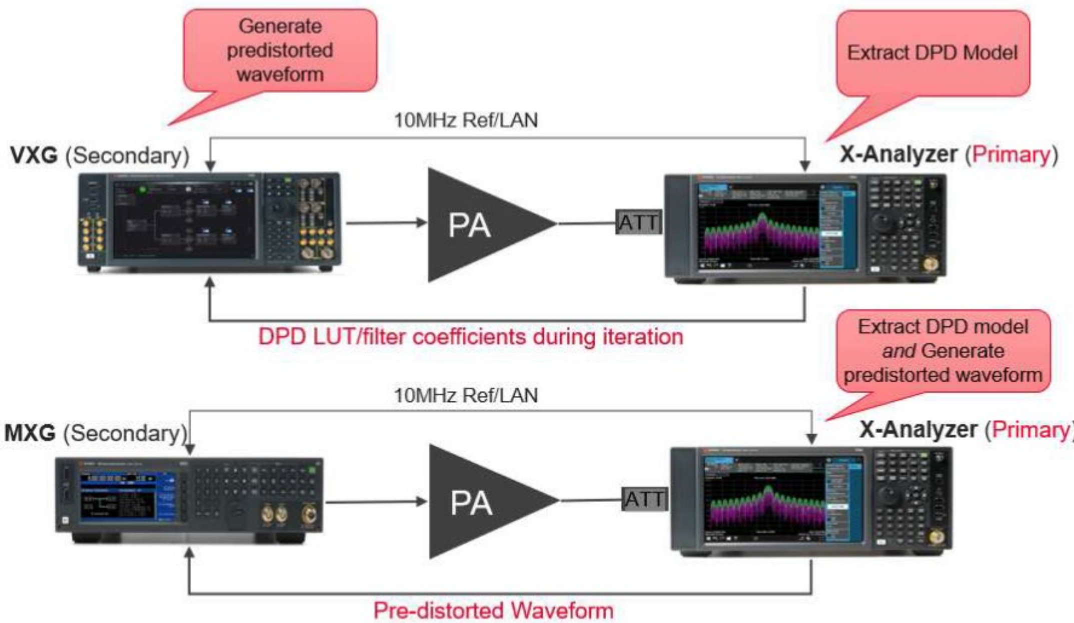


Figure 17. PA test solution #1 – Keysight signal generator plus Keysight signal analyzer

– This solution uses VXT as transmitter and receiver. The algorithms to extract DPD model are integrated in the power amplifier measurement application software, and you can just extract the model or generate the pre-distorted waveform to verify its performance.

Figure 18. PA test solution #2 – Keysight VXT PXIe vector transceiver

- **Measurements for power amplifiers using the Keysight vector network analyzers**

  There is a new approach to distortion measurements that overcomes the challenges of the VSA method:

  – The Keysight PNA-X with the S93072B Internal 6 GHz arbitrary waveform generation application enables active device measurements with modulated signals generated by the Direct Digital Synthesizer (DDS) sources of the PNA/PNA-X.

  – The Keysight PNA-X with a VSG can now characterize nonlinear distortion of a device with a modulated input signal.

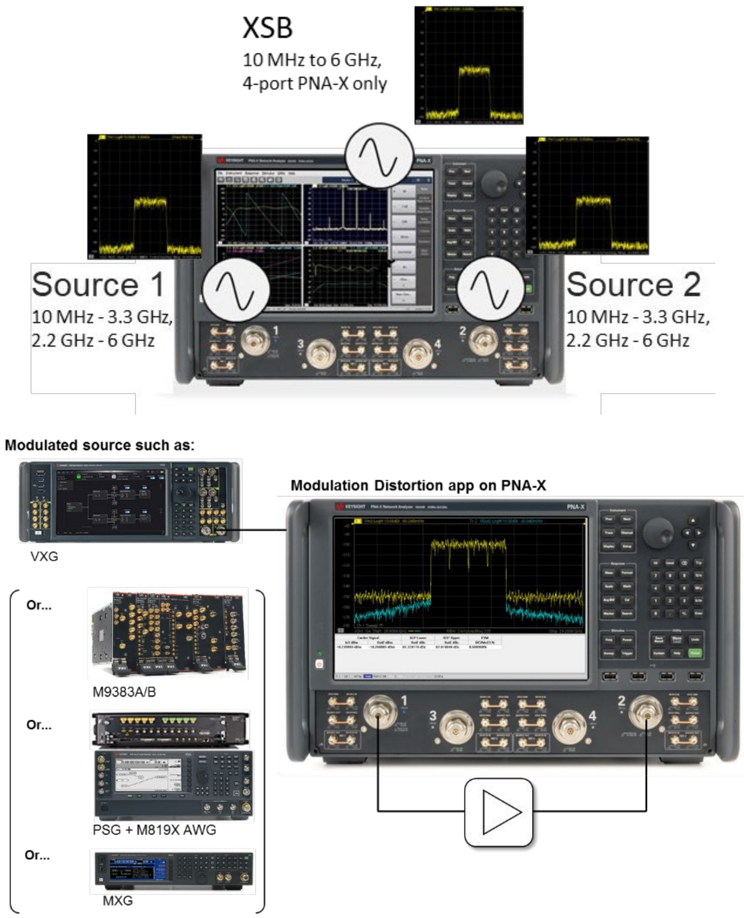


Figure 19. Distortion measurement using the Keysight PNA-X

This new approach, called Modulation Distortion, is in the software application of the PNA-X. The measurement setup is integrated into the PNA-X firmware, which allows you to easily set up the stimulus and measurements and leveraging state-of-the-art calibration techniques for the best accuracy. In addition to existing PNA-X measurements such as S-parameter, Gain Compression, IMD, and Noise Figure, the PNA-X now allows nonlinear distortion measurement under the modulated stimulus condition, without changing connections to the DUT. When characterizing a PA for wide-band applications, it is important to know when the PA starts to show distortion given a specific modulation signal. With the MOD application in the PNA-X, you can accurately measure the performance of the PA with lower residual EVM.

- **RF PA/FEM characterization and test, reference solution**

  This Reference Solution provides high throughput, measurement quality, and performance for design validation and production test of next generation Power Amplifiers/Front End Modules (PA/FEM) supporting cellular and wireless connectivity formats.

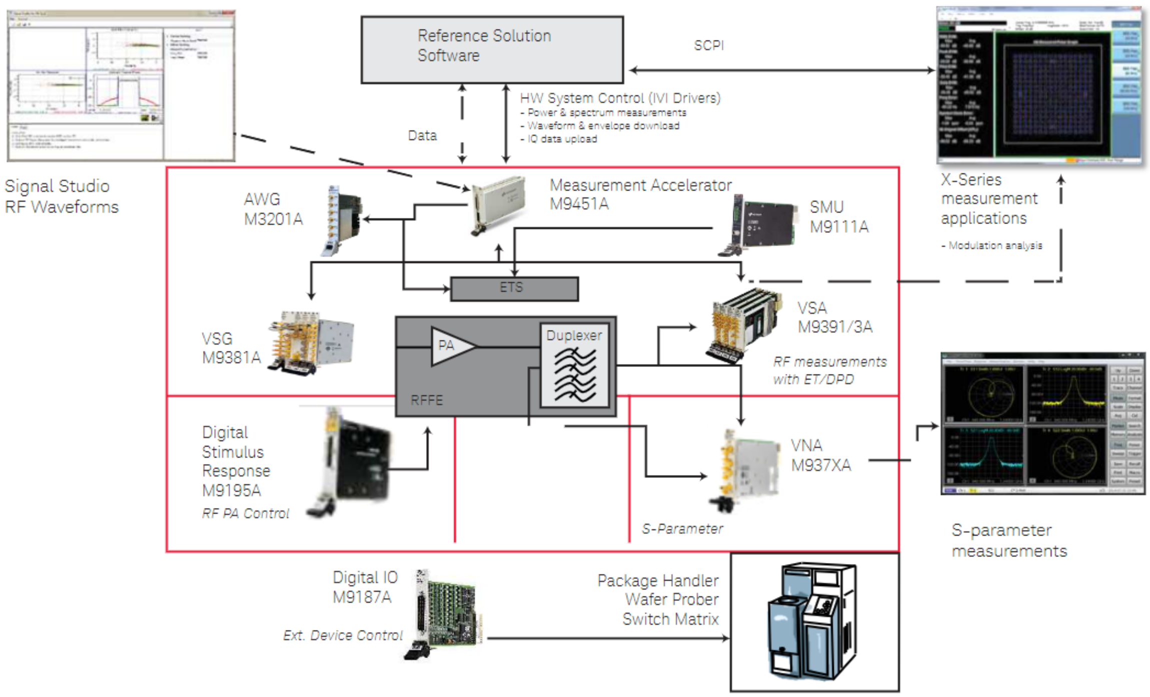


Figure 20. Reference solution architecture for design validation test

- **Customized RF PA automation test solution**

  Keysight also supports customized automation test solutions to meet different customers' specific needs. Below is an example of an RF PA test solution:

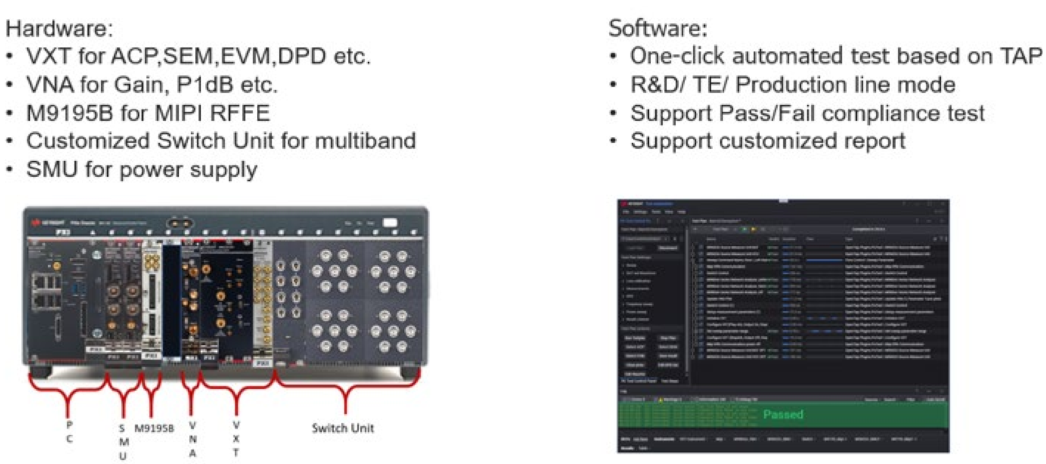


Figure 21. Customized PA test solution

- **Active load control for amplifier modulation distortion application**

  There are several challenges in measuring the distortion in amplifiers:

  – Stimulate the DUT with a real-world modulated input signal.

  – Achieve a high signal-to-noise ratio with linear test receivers.

  – Remove test system error.

  – Able to synthesize any load condition.

  This is where the new application for the PNA-X comes in – to vary the load condition while testing the distortion performance of the amplifier.

  Keysight's active load pull solution allows control of the gamma across the entire modulation bandwidth. The way it works is that the VXG provides the modulated input signal, a1, as well as the modulated output signal, a2, and since it has control over every tone in the a2 signal, the gamma is controlled across the entire modulation bandwidth. The gamma is measured for the bandwidth of interest and the EVM, NPR, and ACPR can be measured as a function of that load.

  Gamma profiles shown are defined as a single point (same gamma across entire bandwidth), a custom gamma profile over the bandwidth (for example, importing a S1P file from ADS), and a gamma with a specified phase shift over the bandwidth.

  – VXG channel 1 provides modulated input signal.

  – VXG channel 2 provides output signal synthesizing load condition.

  – PNA-X MOD channel measures distortion parameters.

  Figure 22 shows a simplified image of the wideband active load pull setup.

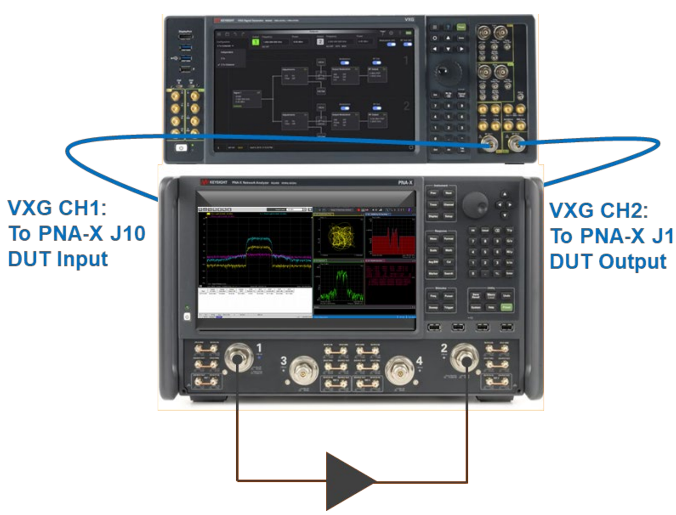


Figure 22. Active load pull setup diagram

The dual channel VXG accurately controls gamma across the entire modulation bandwidth. This allows you to specify a point, a custom profile from an S1P file, or a gamma with a phase shift. Since this application is part of the PNA, the benefits of MOD allow you to overcome wideband measurements challenges and achieve the lowest residual EVM and vector corrected measurements.

Antenna-in-Package (AiP) and Over-the-Air (OTA) test

Several factors contribute to the increasing levels of integration in 5G mmWave devices. These factors are interrelated and are driven by the combination of high frequencies, large numbers of antenna elements, the need to minimize signal path attenuation, and the need to reduce cost.

- **Antenna-in-Package (AiP) test**

  Many 5G designs for mmWave spectrum deployment use antenna-in-package technology to reduce the size and cost of wireless systems and improve Radio Frequency (RF) performance. To properly test AiP designs require a test solution with high output power, ultra-low phase noise, wide analysis bandwidth, and dynamic range. These features improve measurement performance in Over-the-Air (OTA) test at mmWave frequencies for 5G and satellite applications. Here are some challenges for mmwave AiP:

  - Experiencing high path loss at mmWave frequencies.
  - Changing technology now uses wider bandwidths.
  - Challenging to keep up with emerging communication formats.

  A vector signal generator with high power output, for example, can be used with measurement application software to compensate for any system loss. A signal analyzer with high dynamic range and Error Vector Magnitude (EVM) allows you to accurately analyze all 5G New Radio (NR) signal parameters and characterize your AiP design.

  Keysight's solution for testing millimeter-wave AiP technology, as shown in Figure 23, comprises signal generation and signal analysis hardware coupled with measurement application and signal generation software. This integrated testing environment is specifically designed to help you solve your most complex mmWave AiP over-the-air measurement challenges.

Figure 23. Solution for testing millimeter-wave AiP technology

- **Over-the-Air (OTA) test**

  A significant consequence of the increasing levels of integration in 5G mmWave devices is that traditional RF connectors at the boundary between the radio distribution network circuit and the antenna system are no longer possible to implement.

  The push into mmWave frequency bands to access new spectrum for 5G NR is creating an abrupt and significant shift in the way commercial communications devices and systems will be designed and verified. Measurements that were previously implemented using cabled connections are moving to the radiated spatial domain; active beamforming systems, steerable arrays and highly integrated designs will require that virtually all testing at mmWave must be done using radiated OTA methods.

The high level of radio and antenna integration means that much of this testing will be OTA, while the wide variety of test needs (capability, accuracy, size, and cost) requires a correspondingly flexible range of test solutions.

Measurement in the far-field is conceptually the simplest type of OTA measurement system, and is an approved method identified by 3GPP for base station RF measurements and is the baseline UE RF test method. Measurement in the far-field is conceptually the simplest type of OTA measurement system, and is an approved method identified by 3GPP for base station RF measurements and is the baseline UE RF test method.

The Compact Antenna Test Range (CATR) method is recognized as a standard means for far-field characterization. Both far-field and CATR methods can provide comparable far-field measurement shown as shown in the table below:

Attribute	Direct Far-Field	Compact Antenna Test Range
Chamber size	Determined by required far-field distance; Example: 150 mm diameter array at 28 GHz has far-field distance 4.2 m, and chamber length of at least 5.5 m	Determined by required quiet zone diameter; Example: 150 mm diameter array at 28 GHz. Chamber length approximately 2 m
Path loss	Determined by distance between DUT and probe antenna; Example: for a far-field distance of 4.2m at 28 GHz, free-space path loss 74 dB	Determined by focal length of reflector; Example: 150 mm diameter QZ, free-space path loss 58 dB
Cross-polarization isolation	High	~30 dB (curved reflector generates cross-polar component)
Antenna pattern measurements	Measurement accuracy of side lobes and nulls is better at larger distances between DUT and probe antenna	Antenna pattern measurements are equivalent to those measured in direct far-field (Figure 14), measurement accuracy of nulls and side lobes depends on QZ flatness
Position of DUT relative to probe antenna beam	White box: Center of radiation of DUT antenna array must be at center of quiet zone. Black box: Geometric center of DUT must be at center of quiet zone	All DUT antenna arrays must be contained within the quiet zone [18]
Cost	Scales with chamber size	Cost of precision reflector offset by smaller chamber

Keysight OTA chambers span the test base from RF performance with CATRs to SW measurements with small form factor chambers, to end-to-end mobility, and performance with fading using the 3D Multiprobe anechoic chambers.

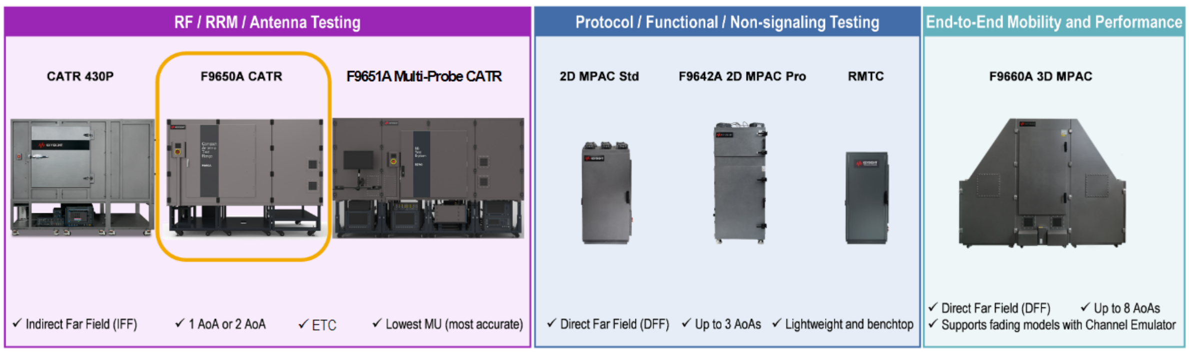


Figure 24. OTA chamber portfolio

For More Information

For further insights and resources, check the following links:

N9055EM0E Power Amplifier Measurement Application

https://www.keysight.com/us/en/product/N9055EM0E/power-amplifier-measurement-application--multi-touch-ui.html

N7614EMBC PathWave Signal Generation for Power Amplifier Test

https://www.keysight.com/us/en/product/N7614EMBC/signal-generation-power-amplifier-test-waveform-playback.html

High Accuracy EVM Measurements for a Power Amplifier Using the PNA-X Series Network Analyzer

https://www.keysight.com/us/en/assets/3123-1277/application-notes/Power-Amplifier-EVM-Measurement-with-PNA-X-Series-Network-Analyzer.pdf

Photonic IC Test

Photonic Integrated Circuit (PIC) and silicon photonics technologies are being used to manufacture devices for optical communications at higher volumes with lower costs, energy consumption, and size. This is now especially driven by the rapidly increasing needs of data centers. These technologies also offer the means to realize new functionality with high-level integration of electronics and optics. Like in the semiconductor electronics industry, appropriate test and measurement at an early stage, like wafer-level test, is valuable to avoid the high cost of processing and packaging substandard devices that will fail the final test as well as for control and diagnostics of the wafer production process. Typically, this involves parametric tests to characterize the material and structuring quality, like measuring sheet resistance and capacitance electrically and attenuation and responsivity optically.

Optical testing generally also includes dependence on wavelength and on the alignment of optical polarization with the waveguide structures. For transponder devices like photodetectors and modulators, the RF-frequency dependence is also important for characterizing the bandwidth of the devices. The diagram below shows a PIC typical measurement setup:

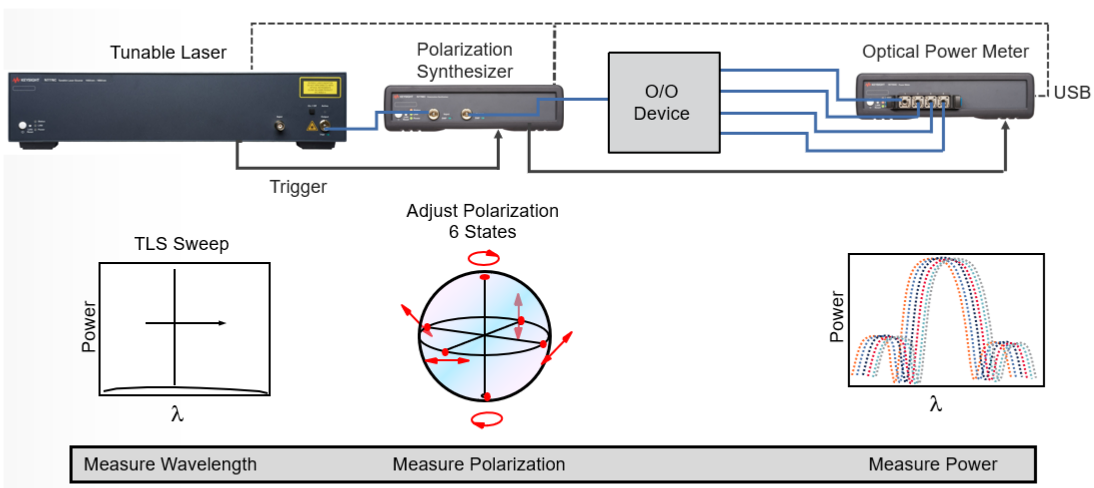


Figure 25. Photonic Integrated Circuits (PIC) typical measurement setup

Passive Optical Component Test

Passive optical component testing is essential to ensure that these components meet the required specifications and standards for their intended use. For example, passive optical component testing is crucial in ensuring the reliability and performance of optical networks, particularly in high-speed data transmission applications. By testing these components, network operators and service providers can ensure that their networks are operating at optimal efficiency, minimizing downtime, and providing high-quality services to their customers.

There are several challenges in passive optical component testing.

- **Accuracy and repeatability**: Passive optical components are designed to operate at very high speeds and with low loss, so accurate and repeatable testing is critical. However, the performance of these components can be affected by factors such as temperature, humidity, and mechanical stress, which can make accurate and repeatable testing challenging.

– **Complexity**: Passive optical components can be complex and testing them can require a high level of expertise and specialized knowledge. This can make it challenging for organizations to find qualified personnel to perform the testing, or to train existing personnel to perform the testing correctly.
– **Compatibility**: Passive optical components can be designed using different technologies and materials, and this can affect their compatibility with different testing equipment. Ensuring that the testing equipment is compatible with the components being tested can be challenging and can require careful selection of both the components and the testing equipment.

To address those challenges, Keysight provides passive optical components test solution, including the N7700100C Photonics Application Suite (PAS) turnkey measurement solution. The N7700100C PAS engine enables fast single sweep polarization resolved measurements using a 6 State Mueller Matrix approach. The parameters characterized over wavelength for optical-to-optical devices include Insertion Loss (IL), Polarization Dependent Loss (PDL), and the TE/TM insertion loss for principle states of polarization. The N7700100C PAS engine can also integrate three N777xC tunable lasers with an optical switch, N7731C, to perform an all-band polarization resolved sweep from 1240 to 1650 nm.

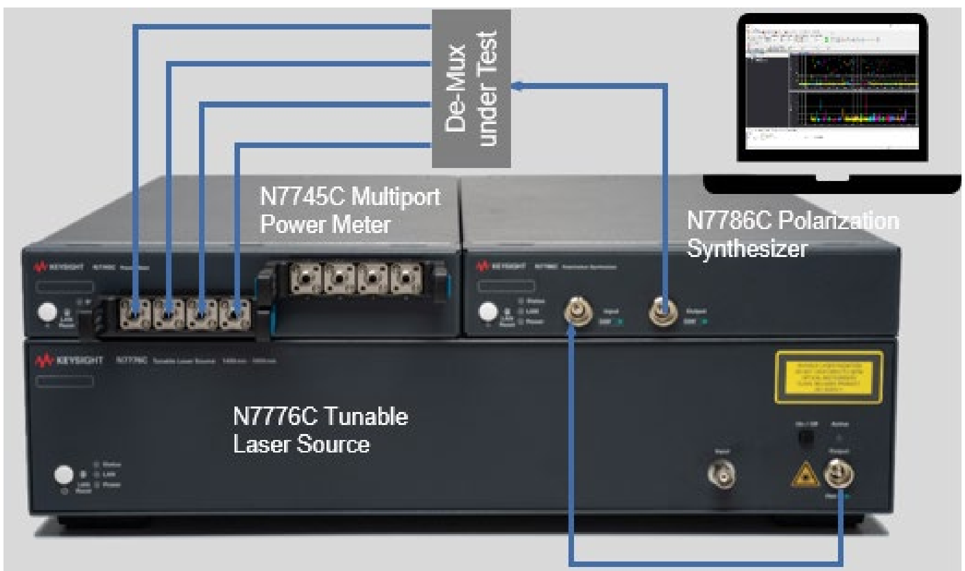


Figure 26. Passive optical components test solution

Active Optical Components Test

Active optical component testing refers to the process of evaluating the performance and characteristics of active optical components, such as Receiver Optical Sub Assembly (ROSA). It is basically a component that is used to receive optical signals in fiber optic system. The ROSA consists of photodiode device that converts light into electrical signal. Compared with passive optical components, active optical component testing presents more challenges since it needs an external power source to function and is designed to generate, amplify, or modulate optical signals.

Keysight’s active optical components test solution, as shown in Figure 27, is built based on passive optical components test solution and replaces power meters by Source/Measure Units (SMU) to test photodetectors. The parameters characterized over wavelength for optical to electrical devices include responsivity (mA/mW), polarization dependent responsivity and TE/TM responsivity for principle states of polarization. Similar to optical-to-optical devices, the N7700100C PAS engine can integrate three N777xC lasers for an all-band polarization resolved sweep from 1240 to 1650 nm.

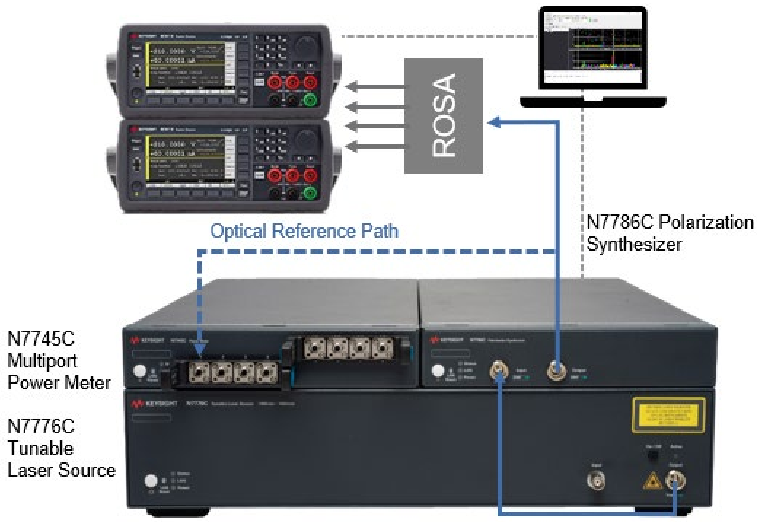


Figure 27. Active optical components test solution

E/O and O/E Measurement

As light wave transmission systems become more advanced, component designers and manufacturers must maximize the performance of their devices. For example, one parameter often used to specify digital system performance is bit error rate. However, it is difficult to specify individual components in such terms. Rather, fundamental measurements such as gain, bandwidth, frequency response and return loss can be appropriate. The Lightwave Component Analyzer (LCA) is used to measure the linear electro-optic transmission and electrical reflection characteristics of a component as a function of modulation frequency.

- **E/O measurements (modulators, lasers, LEDs)**
  The measurement of an E/O transducer is a combination of input modulating current or voltage and output optical modulation power. For current converting devices, the slope responsivity is used to describe how a change in input current produces a change in optical power. An LCA measures input modulating current and output modulation power and displays the ratio of the two in Watts/Amp, either linearly or in decibels.

- **O/E measurements (photodiodes and receivers)**
  The measurement process for O/E devices is similar to E/O devices. The measurement consists of the ratio of output electrical modulation current to input optical modulation power. Slope responsivity for O/E devices describes how a change in optical power produces a change in electrical current. The LCA measures the input optical modulation power and output modulation current and displays the ratio of the two in Amps/Watt.

- **O/O measurements**

  Characteristics of purely optical devices can also be measured. In this case, both the stimulus and response are modulated light. The ratio measurement is simply one of gain or loss versus modulation frequency.

  Keysight provides traceable turn-key solutions, as shown below, for S21 and S11 characterization of E/O and O/E components and 1310/1550 nm single mode solutions to 110 GHz, 850 nm multimode solutions to 50 GHz.

Figure 28. High-speed lightwave component analysis solution

For More Information

For further insights and resources, check the following links:

Wafer and Chip-Level Optical Test

https://www.keysight.com/us/en/assets/7018-06296/application-notes/5992-3258.pdf

High Speed Lightwave Component Analysis

https://www.keysight.com/us/en/assets/7018-01732/application-notes/5989-7808.pdf

Polarization-Resolved Measurements using Mueller Matrix Analysis

https://www.keysight.com/us/en/assets/7018-01231/application-notes/5989-1261.pdf

Semiconductor Teaching Lab Solution

The semiconductor industry has become the cornerstone of modern technology, driving advancements in diverse fields such as communications, healthcare, automotive, and renewable energy. As emerging trends like Artificial Intelligence (AI), the Internet of Things (IoT), and 5G communications continue to surge, semiconductors remain at the heart of innovation.

This technological evolution has created an unprecedented global demand for skilled professionals who can design, optimize, and understand these critical components. Consequently, governments and industries worldwide are significantly increasing investments to secure a steady pipeline of semiconductor talent.

UU101LAB – Basic Design and Measurement

The solution consists of three comprehensive labs that transition from fundamental device characterization to advanced circuit design and optimization. This teaching solution provides:

- **Fundamental understanding**: Gain a deep understanding of the internal structures, physical mechanisms, and operating principles of LEDs, BJTs, and MOSFETs.
- **Practical measurement**: Learn to perform precise electrical measurements using industry-standard instrumentation.
- **Circuit design and optimization**: Master the use of Advanced Design System (ADS) software for the design, simulation, and multi-objective optimization of active mixers and FET-based amplifiers.
- **Industry readiness**: Bridge the gap between theoretical semiconductor physics and practical engineering implementation.

This creates a strong foundation that prepares students and institutions for more advanced characterization topics without overwhelming beginners.

B2902C SMU   Digital Learning Suite   Advanced Design System   Lab Sheets

Figure 29. Components of *Module 1: Basic Design and Measurement*

Lab	Hours	Title	Learning Outcomes
1	3	Basic Semiconductor Devices and Measurement	Understand Semiconductor Devices: Measure the IV curve of LEDs, BJTs, MOSFETs to obtain parameters, such as IV curve, Gummel plot and output characteristic curve.
2	3	Low-Power Single-Transistor Active Mixer Design	Understand Active Mixer Design: Follow a comprehensive process that includes bias network design, large-signal verification, matching circuit design, creating layout for mixer design and more.
3	6	Amplifier Design Based on FET	Understand FET Amplifier Design: Build the FET amplifier schematic and symbol, perform DC and AC simulations, design matching network, conduct stability analysis, optimize/fine tune the amplifier.

For More Information

For further insights and resources, visit https://www.keysight.com/us/en/product/UU101LAB/semiconductor-basic-design-and-measurement.html.

UU102LAB – Parametric Test and On-Wafer Measurement

This solution is designed to provide students with comprehensive hands-on experience of core semiconductor device testing technologies and industrial standard workflows through a series of progressive practical labs.

The labs aim to develop students' proficiency in operating the Keysight B1500A Semiconductor Device Parameter Analyzer and probe stations. Students will gain deep insights into MOSFET I-V characteristics (Id–Vd, Id–Vg), Threshold Voltage (Vth) extraction, Capacitance-Voltage (C–V) measurement, and ultra-low current (pA/fA level) detection techniques.

By completing the UU102LAB, students move beyond button-pushing and develop a true understanding of the importance of measurement quality and methodology.

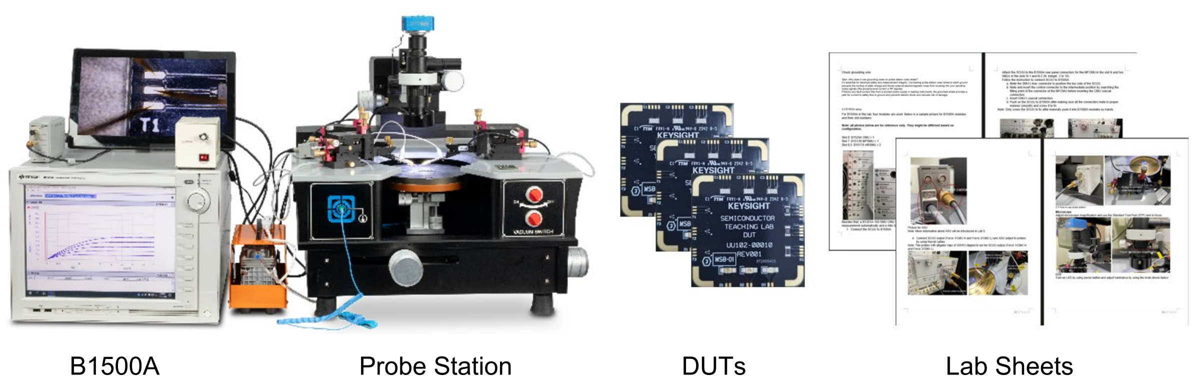


Figure 30. Components of *Module 2: Parametric Test and On-Wafer Measurement*

Lab	Hours	Title	Learning Outcomes
1	3	Hardware Setup and Software Basic	Set up the B1500A system, probe station, and EasyEXPERT software to perform reliable parametric measurements.
2	1	Id–Vd Application Test	Perform Id–Vd measurements to understand MOSFET output characteristics and identify cutoff, linear, and saturation regions.
3	2	Vth Measurement in Classic Test	Execute Id–Vg sweeps in Classic Test mode to extract and analyze MOSFET threshold voltage (Vth).
4	2.5	C–V Measurement	Conduct C–V measurements and apply calibration techniques to accurately analyze device capacitance characteristics.
5	2.5	Ultra-Low Current Measurement	Configure the system for ultra-low current testing and measure picoamp-level leakage with optimized noise reduction.
6	1	Sampling Measurement	Use time-domain sampling to analyze transient and pulsed I/V behavior while minimizing self-heating effects.
7	1	Id–Vg Tracer Test	Perform fast, interactive Id–Vg characterization using Tracer Test mode and extract Vth with pulsed measurements

For More Information

For further insights and resources, visit https://www.keysight.com/us/en/product/UU102LAB/semiconductor-parametric-test-and-on-wafer-measurement.html.

UU103LAB – Photonics IC Measurement

Photonic Integrated Circuits (PICs) represent a transformative leap in optical technology, enabling the miniaturization of complex optical systems (such as lasers, waveguides, modulators, and detectors) into compact, energy-efficient microchips. As these platforms become essential for high-performance applications in data centers, quantum computing, and artificial intelligence, there is an increasing demand for skilled professionals capable of designing and measuring on-chip components.

This teaching lab curriculum is designed to provide students with the foundational expertise required for advanced photonic device testing and optical coupling optimization.

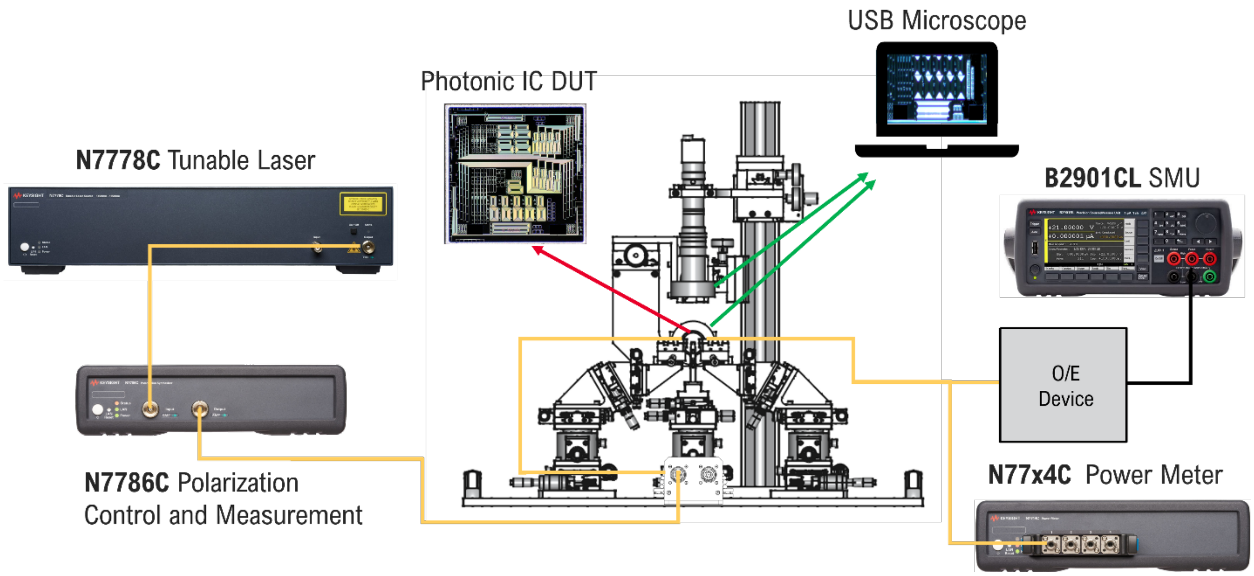


Figure 31. Components of *Module 3: Photonics IC Measurement*

Lab	Hours	Title	Learning Outcomes
1	3	Getting Started – Probe Station Operation	Fiber cleaving, probe station 6-axis alignment, and PIC die handling.
2	3	Fixed Wavelength Power Measurements and Insertion Loss	Absolute power, photodetector responsivity, and on-chip waveguide loss using the cutback method.
3	3	Swept Wavelength Insertion Loss	Instrument synchronization, swept wavelength IL, and characterization of Mach Zehnder Interferometers (MZI) and Ring Resonators.
4	3	Polarization Control and Measurement	State of Polarization (SOP) manipulation, Poincaré sphere visualization, and measuring PDL via the All-States method.
5	3	Swept Wavelength Insertion Loss (IL) and Polarization Dependent Loss (PDL)	Mueller Matrix method for single-sweep polarization resolved traces and angular dependence of grating couplers.
6	3	Swept Wavelength Optical to Electrical (OE) PIN Diode Responsivity	Integrating Source Measure Units (SMUs) to calculate responsivity (A/W) and Dark Current.

RFIC Simulation and Measurements Experiment Examples

Introduction

Keysight's RFIC simulation and measurement experiment, U3851A RF Microwave Circuit Design, Simulation and Measurement Courseware, 5G NR n3, focuses on end-to-end RF circuit design flow, and integrates industry-oriented and real-world examples to prepare students for emerging technology trends. The lab courseware comes with a modular prototype kit utilizing a 1.8 GHz receiver module – a 5G New Radio n3 band – as well as lab sheets and assignments that focus on the complete physical design spectrum, from specifications and simulation to prototype building and validation.

Through RFIC simulation and measurement experiment, students learn how to design an RF product end-to-end, from specification and simulation, to prototype building and validation. Students will develop practical skills in using industry-standard test and measurement instruments such as oscilloscopes, network analyzers, signal generators, and spectrum analyzers. They will also learn how to design an RF receiver with Keysight's industry-leading Electronic Design and Automation (EDA) software including PathWave Advanced Design System (ADS) and PathWave System Design (SystemVue).

U3851A establishes a solid foundation in RF microwave fundamentals, paving the way for the student's specialization in advanced 5G or IoT wireless applications. Such practical skills and real-world application knowledge gained through the courseware will make students industry-ready and highly sought-after.

– Delivers lab courseware that covers the entire RF system design lifecycle
– Helps university professors save time and resources by expanding current engineering programs
– Helps universities easily integrate the lab courseware into the current curriculum
– Ensures students are fully updated with the latest developments in engineering

The Training Kit consists of the modular prototype kit, kit controller, RF adapters and splitter, cables (RF, power, LAN, BNC), power adapter, and carry case.

Table of Experiments

– Transmission lines
– Filters
– Low noise amplifier
– Driver and power amplifier
– Oscillator and synthesizers
– Mixers
– 5G receiver

Figure 32. RF circuit design, with elements of 5G New Radio n3

Hardware and Software

Required Keysight instruments

- Signal generator: N5171B EXG Signal Generator – 503, UNM
- Spectrum analyzer: N9000B CXA Analyzer – 507, N9068C
- Network analyzer: N9917A FieldFox VNA – 210, 211, 010, 233, 235 option
- Noise source: 346B Noise Source – 100
- Power Supply: E36312A – STD option
- Oscilloscope: DSOX1102G – DSOX1B7T102
- 85521A calibration kit, 4-in-1 open, short, load and through, DC to 26.5 GHz, 3.5 mm (f) – STD option

Required Keysight Design and Automation software with Keysight instruments

- PathWave ADS
- PathWave Genesys
- PathWave EMPro
- PathWave SystemVue
- FieldFox Data Link Software

Power Electronics EMI Experiment Examples

Introduction

The Power Electronics EMI Laboratory is an introductory EMI Curriculum for Electrical and Electronic Engineering Undergraduate Program. The experiments provide guidance to the Keysight Power Electronics EMI Laboratory, a hands-on learning experience on fundamentals of EMI in Power Electronics.

The case studies offered in the Laboratory are intended to stimulate the investigation and understanding capabilities of students, beyond the learning of the specific technical topics treated in the experiments.

Behavioral models of devices, circuit simulations, and experimental tests are the ingredients of the experiments, focusing on the roots of EMI issues in real world power electronics applications.

The experiments are organized according to the following sequence of steps:

1. Introduction
2. Theory background
3. Exercise
4. Simulations
5. Measurements
6. Experiment check-out
7. Learning resources
8. Answer key

Table of Experiments

- **Basic operation of a DC-DC hysteretic buck regulator**
  The experiment is executed by using the LM3475 Section of TI-PMLK BUCK hardware platform for experimental measurements and the ADS PMLK-LM3475-Exp1 schematic for simulations, to analyze the operation and the main waveforms of a DC-DC hysteretic buck regulator in terms of switching frequency and relevant harmonics of interest for EMI.

- **Impact of power MOSFET on DC-DC buck regulator EMI**
  The experiment is executed by using the LM3475 Section of TI-PMLK BUCK hardware platform for experimental measurements and the ADS PMLK-LM3475-Exp2 schematic for simulations, to analyze the impact of MOSFET capacitances and resulting switching speed on the EMI of a DC-DC buck regulator.

- **Impact of input capacitance de-rating and PCB layout inductances on conducted EMI – hysteretic regulator**

  The experiment is executed by using the LM3475 Section of TI-PMLK BUCK hardware platform for experimental measurements and the ADS PMLK-LM3475-Exp3 schematic for simulations, to analyze the impact of input capacitances de-rating and resulting degradation of input filter attenuation on the EMI of a DC-DC buck hysteretic regulator.

- **Impact of input capacitance de-rating and PCB layout inductances on conducted EMI – peak-current regulator**

  The experiment is executed by using the TPS54160 Section of TI-PMLK BUCK hardware platform for experimental measurements and the ADS PMLK-TPS54160-Exp4 schematic for simulations, to analyze the impact of input capacitances de-rating and resulting degradation of input filter attenuation on the EMI of a DC-DC buck peak-current regulator.

- **Impact of inductor saturation on conducted EMI – hysteretic regulator**

  The experiment is executed by using the LM3475 Section of TI-PMLK BUCK hardware platform for experimental measurements and the ADS PMLK-LM3475-Exp5 schematic for simulations, to analyze the impact of inductor saturation on the operation and resulting EMI of a DC-DC buck hysteretic regulator.

- **Impact of inductor saturation on conducted EMI – peak-current regulator**

  The experiment is executed by using the TPS54160 Section of TI-PMLK BUCK hardware platform for experimental measurements and the ADS PMLK-TPS54160-Exp6 schematic for simulations, to analyze the impact of inductor saturation on the operation and resulting EMI of a DC-DC buck peak-current regulator.

- **Impact of peak-current-control instability on EMI**

  The experiment is executed by using the TPS54160 Section of TI-PMLK BUCK hardware platform for experimental measurements and the ADS PMLK-TPS54160-Exp7 schematic for simulations, to analyze the operation, the main waveforms, the subharmonic operation, and the instability of a DC-DC peak-current-controlled buck regulator and resulting effects on EMI.

- **Impact of PCB capacitances on EMI**

  The experiment is executed by using the TPS54160 Section of TI-PMLK BUCK hardware platform for experimental measurements and the ADS PMLK-TPS54160-Exp8 schematic for simulations, to analyze the impact of PCB parasitic capacitances between the power train and the control circuitry on the operation of a DC-DC buck peak-current regulator and resulting EMI effects.

Hardware and Software

The experimental measurements described in the Power Electronics EMI Laboratory are performed by means of the following Keysight instruments and software:

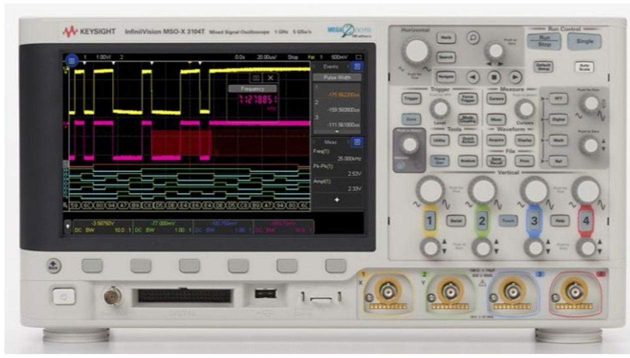


Figure 33. Keysight MSOX3104T oscilloscope

Figure 34. Keysight E36234A DC power supply

Figure 35. Keysight EL34243A DC electronic load

Figure 36. Keysight 1147B current probe

Figure 37. PathWave Advanced Design System (ADS)

Digital Learning Suite (DLS) in IC Research and Teaching

Keysight's digital platform – the Keysight SR101EDUA Digital Learning Suite (DLS) – is specially designed to help researchers and educators accelerate and optimize IC related process. DLS allows you to control instruments remotely with test automation capabilities. For educators, the lab management and collaborative learning function in DLS will ensure a more efficient teaching process. And finally, with the latest learning resources at your fingertips, you can now keep up with current industry trends of the world.

The SR101EDUA Digital Learning Suite offers a convenient way to transition to online learning. This end-to-end solution is designed for a complete remote setup of a basic instrument lab and covers all requirements and needs, from web-based lab management and scheduling administration to instrument control and remote access for measurement and analysis. And as students continue to work with industry-grade test and measurement instruments and software, they will gain practical skills and application knowledge similar to industry engineers conducting their work in the lab today.

Test Automation

Test automation is heavily used in the R&D and production environment in the test and measurement industry. In education, educators and students use test automation to characterize electronic designs, and to complete group assignments or research projects. Without the support from an easy-to-use development environment, scripting test automation is challenging especially when it involves the integration of multiple remote instruments and DUT controls, interactive user interfaces, advanced data processing, and charting. Often, students also need access to lab equipment out of lab hours to continue with their lab work. It is crucial to have a test automation environment that can be accessed anywhere and anytime, equipped with a remote lab management and scheduler.

The PathWave Test Automation (powered by OpenTAP) is the core automation engine powering many Keysight solutions in automating measurements in fields such as 4G, 5G, Automotive, Cybersecurity, etc. The PathWave Test Automation OpenTAP engine is now built into the new web-based Digital Learning Suite (DLS) to ease the use of test automation for educators and students in a hybrid learning environment.

- Industry-grade test sequencer with integrated web interface to control instruments and characterize designs.
- Versatile charting tool to visualize, compare, analyze, and share test results in different formats.

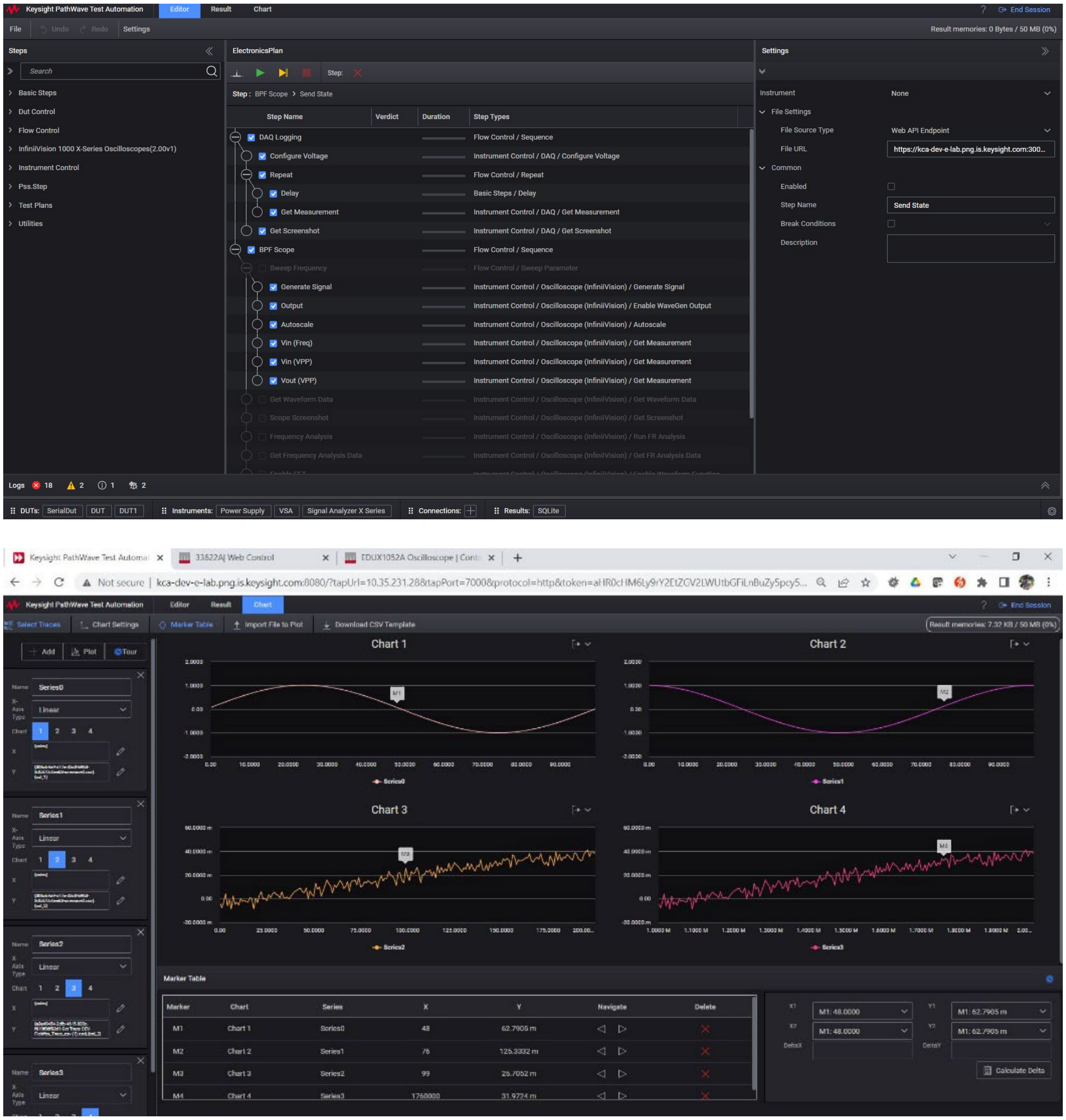


Figure 38. Examples of an IC Teaching Lab

Soft Front Panels

The Soft Front Panel (SFP) is a Graphical User Interface (GUI) application that provides a way to control and interact with test and measurement instruments like oscilloscopes, spectrum analyzers, signal generators, and other lab equipment. In modern LXI (LAN eXtensions for Instrumentation) instruments, the soft front panel is integrated into the built-in instrument web server, allowing for easier remote control and interaction with the instrument.

Apart from the soft front panel, you can also view and save instrument settings, do screenshots, perform firmware update as well as send SCPI commands, all through the web server. In DLS, you can add and manage multiple LXI instruments centrally from a single platform. Besides serving as a gateway to instrument web servers, DLS can also be used to manage Windows-based instruments where remote graphical access is typically done through Remote Desktop Protocol (RDP) or Virtual Network Computing (VNC).

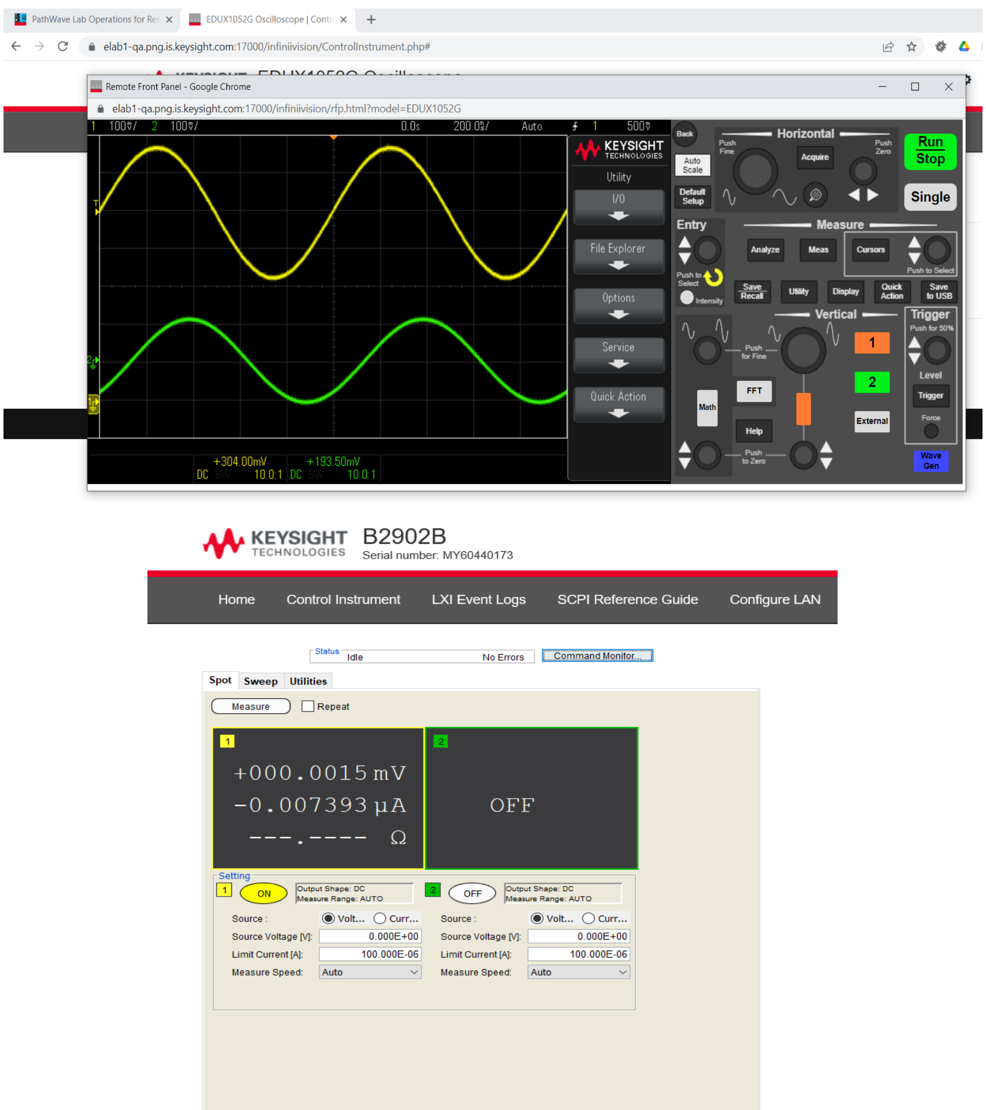


Figure 39. Example of a soft front panel

Remote and Collaborative Learning

The Digital Learning Suite enables remote learning and collaboration, allowing students to access lab resources, share data, and collaborate with peers, regardless of their physical location.

DLS optimizes remote and collaborative learning experiences by offering multi-user remote access with a built-in scheduler. This feature is specifically designed to enhance hybrid collaborative learning, providing a seamless and efficient learning environment for students and educators.

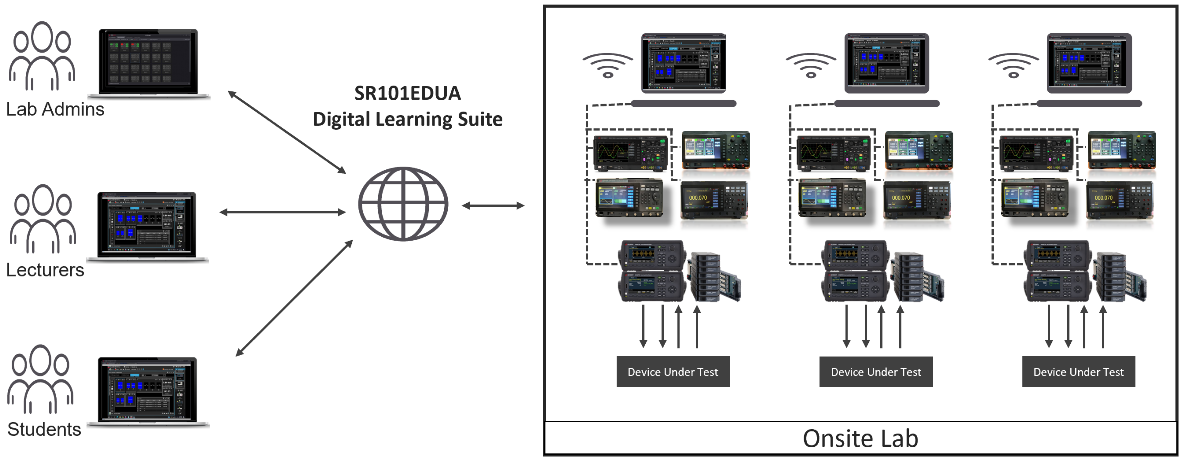


Figure 40. The Hybrid Lab solution

By simply utilizing a web browser, you have the active capability for multi-user access to remotely enter the lab and control all the equipment functionalities, offering a seamless and immersive experience as if you were physically present in the lab itself. The user-friendly web-based interface allows you to interact with the equipment, adjust settings, initiate measurements, and observe real-time data streams, enabling all participants to actively engage in lab activities from any location with an Internet connection.

This multi-user remote accessibility not only provides convenience but also breaks down geographical barriers, allowing students, educators, and researchers to collaboratively participate in laboratory experiments, regardless of their physical distance.

Some of the unique features include:

– Up to five (5) concurrent remote bench desktop access
– Chatroom
– File transfer
– Example in an IC teaching lab

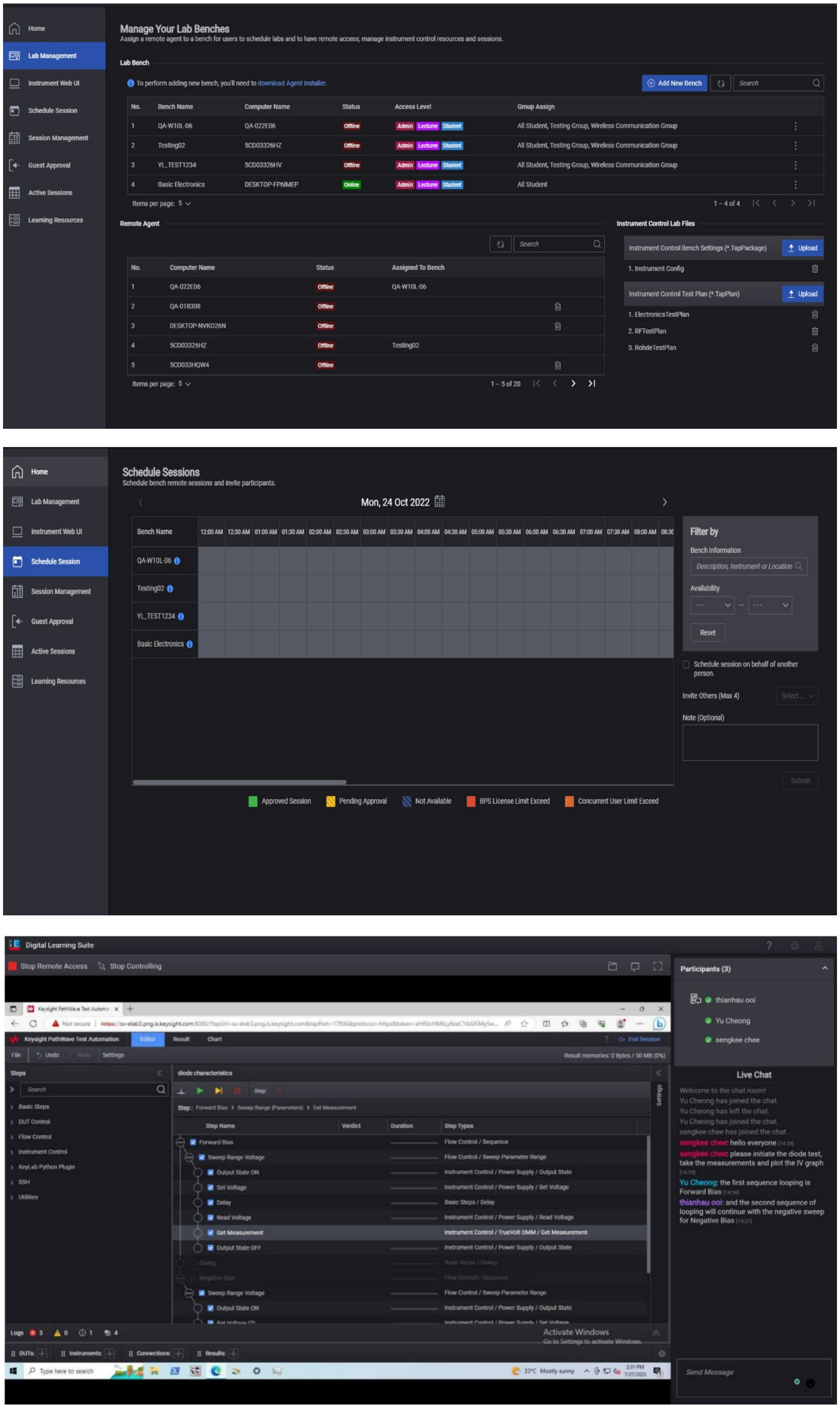


Figure 41. Lab management, session scheduling, and chat room

Learning Resources

Embrace the future of teaching and learning with readily available contents and actively unlock the vast potential of on-demand, industry-relevant knowledge. Explore thousands of on-demand industry-relevant Keysight University's learning resources with ease and access a diverse collection of learning materials, including resources from various industries, instrumentation guides, courseware, and application notes from different sectors. These valuable insights and knowledge are readily available to cater to specific interests and needs.

Some contents are sourced from industry experts, while others are developed by Keysight's in-house team of experienced educators and engineers.

– Keysight University courses
– Instrument user manuals
– Lab sheets (RF, IoT, digital communication, etc)

All content can be easily and seamlessly integrated into the University Learning Management Systems (LMS) via LTI Deep Linking.

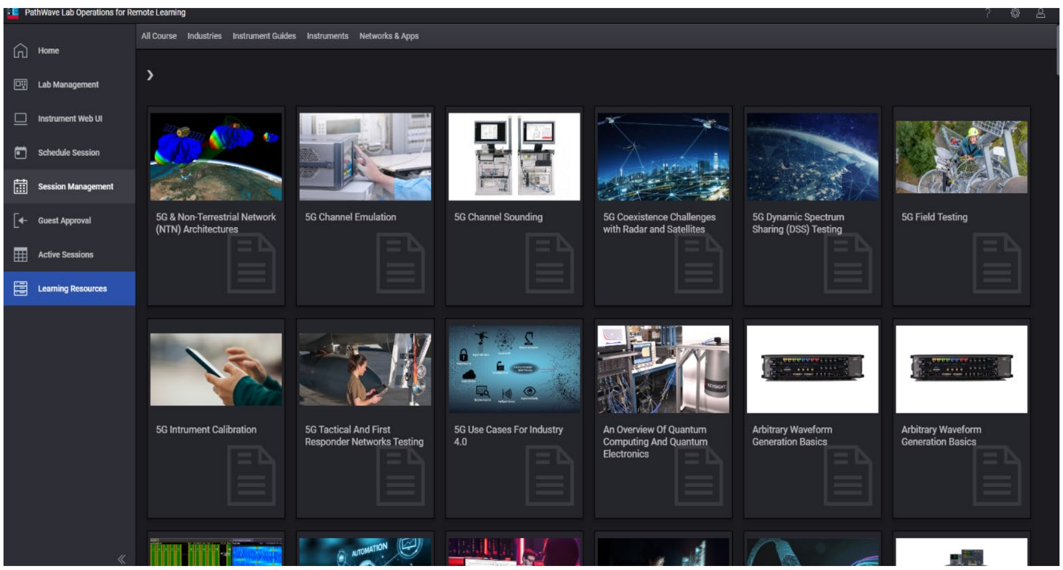


Figure 42. Learning resource

Students can access a diverse collection of learning materials and take full control of their learning journey by engaging with these resources on their own terms. With easy access to these comprehensive resources, they can choose when and where to learn to suit their schedule and preferences, and actively continue their learning journey from where they have stopped.

For More Information

Visit https://www.keysight.com/us/en/product/SR101EDUA/digital-learning-platform.html to learn more about the Keysight SR101EDUA Digital Learning Suite (DLS).

For more insights on how to easily create test automation with DLS, check the following link:

https://www.keysight.com/us/en/assets/3123-1368/application-notes/Create-Test-Automation-without-Programming.pdf

https://www.keysight.com/us/en/assets/3123-1383/application-notes/Instrument-Control-and-Automation-with-Python.pdf

You can also take a quick tour of this software here: https://keysight.tourial.com/pages/0737d39c-cce0-4ac1-bfd3-e14d52d04425