Streamlining Optical Control and Characterization with Software-Defined Instrumentation

FPGA-based, software-defined equipment can help labs customize system applications and save on costly resources.

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INTRODUCTION

Using multiple standalone pieces of test equipment for characterizing and controlling optical systems, a common practice, can lead to frustrating issues arising in the lab. Having too many components in a system can be financially taxing, delay timelines due to complexity, and take up precious benchtop space. Cluttered systems are common in labs making measurements with very low signal-to-noise ratios (SNR), performing phase measurements and locking, or performing laser frequency stabilization, requiring a more streamlined approach for these methods. Fortunately, as technology rapidly advances, it's becoming easier to customize equipment and systems to cater to the specific needs of each lab. This report will cover how field programmable gate array (FPGA)-based, software-defined test equipment—like the Moku family of devices from Liquid Instruments—can help labs avoid common roadblocks in the field of optical control and characterization.

OPTICAL EXPERIMENT CHALLENGES

Many applications and research fields are challenged by complex setups in the lab. Beyond a high number of necessary optical and measurement components, labs may additionally require lock-in amplifiers, proportional–integral–derivative (PID) controllers, arbitrary waveform (AWG)/waveform generators, oscilloscopes, or data loggers.

Additionally, it can be arduous to determine how to connect or configure different components. For example, different connections may be needed for controlling an experiment as opposed to troubleshooting and characterizing an experiment.

It is also common for labs to notice a shift in requirements as an experiment unfolds. It may be difficult to know what materials are required prior to the experiment beginning, or perhaps a roadblock along the way calls for a

piece of equipment that the lab had originally deemed unnecessary. This is also a common issue in emerging fields where the specialized equipment doesn't yet exist or is difficult to obtain, which means that labs often must build their own instruments. By the time the budget is updated and approved, and the new equipment is ordered or created, timelines will be negatively impacted, and progress will be stalled.

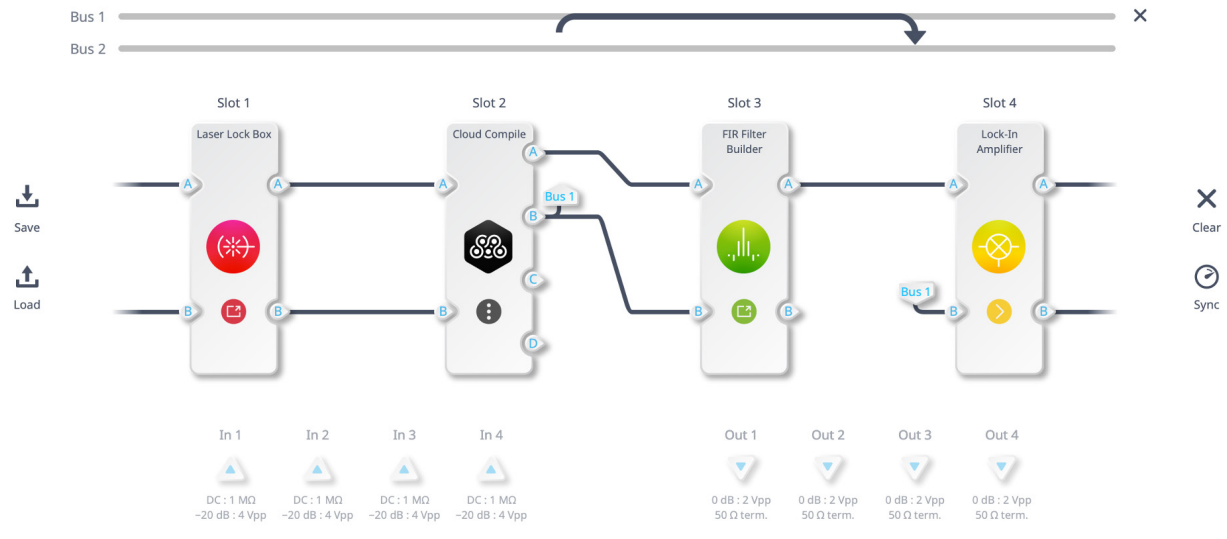
SOFTWARE-DEFINED, FPGA-BASED TEST EQUIPMENT FOR SRS MICROSCOPY

During stimulated Raman scattering (SRS) experiments, labs often deal with very low signals that require specific add-ons, like a boxcar averager, to ensure better results. SRS setups are sensitive to noise and are difficult to scale; if a setup requires additional beams or disturbance rejection, this will cost time and money. In addition, when performing two-color SRS, there should be multiple lasers in use, meaning multiple lock-in amplifiers must be acquired, which also consumes a great deal of financial and spatial resources. SRS experiments act as a perfect use-case example that demonstrates how FPGA-based test equipment can help labs overcome these challenges.

The introduction of software-defined, FPGA-based test equipment in the lab allows for a reconfigurable system. By using this type of equipment, labs can deploy multiple, independent lock-in amplifiers, view their graphs in real time simultaneously, and scale quickly by leveraging additional custom or integrated instruments. The flexibility of this equipment makes it ideal for niche applications and emerging fields. Users can deploy their own code for virtually any additional custom signal processing, meaning they can avoid complex new setups (**FIGURE 1**). By using FPGA-based instrumentation, labs can run multiple instruments on a single device without adding extra cabling, noise, or instability. Essentially, the system's resulting flexibility will lend labs more control over their experiments.

This versatile equipment also acts as a time saver. Because these instruments are software-defined, upgrades and further customization can be implemented via software updates. Additionally, labs often run into roadblocks over the course of an experiment that then require the system to offer more functionality than previously needed. Instead of waiting for additional hardware to be ordered and shipped,

FIGURE 1: Scaling optical control systems with software-defined instrumentation.



labs can add another function to their system instantly with software-defined instrumentation. This will also help with budgeting, as updating or reconfiguring software is notably less expensive than purchasing new hardware.

In SRS experiments, the spectral range is typically limited by the laser bandwidth. Scanning through wavelengths with a tunable laser is the common workaround, but this solution is slow and incompatible with time-sensitive experiments, such as live-cell imaging. Another workaround could be to employ a third laser beam to scan a different Raman transition region; this would require separate detectors and lock-in amplifiers for each beam, again costing labs money and benchtop space.

If the lab uses Multi-instrument Mode, or a partitioned FPGA, on Moku:Pro, two lock-ins can be used on one device and either share a reference or use separate references. **FIGURE 2** shows an example of a two-slot setup in which Input 1 takes the detected signal from the first photodiode while Input 2 acts as the reference signal, and Input 3 in the second slot takes the detected signal from the second photodiode.[1] This setup supports simultaneous imaging even if there is a large wave number difference, allowing for dual-channel imaging in a compact system.

FIGURE 3 shows how an optical control system can be optimized with or replaced by software-defined instrumentation. This Pound–Drever–Hall (PDH) setup, which is a common electro-optic control system, is complex and difficult to build. Multiple signal generators, PID controllers, a frequency response analyzer, and additional filters may be required to ensure system performance, but with Moku, all these pieces can be replaced by a single device. A standalone laser lock box can be used to drive and stabilize a system, and labs can further customize the setup by including certain components within the laser lock box. The connections between the instruments are lossless, low-latency interconnects that remain on the FPGA, meaning the system behavior is not being changed by adding these instruments. Moreover, instruments can be swapped, and connections can be rerouted on the FPGA without touching the physical setup.

THE MOKU FAMILY OF RECONFIGURABLE DEVICES

Liquid Instruments offers three hardware devices that each support a suite of 13 integrated instruments for one seamless software experience: Moku:Go, Moku:Lab, and Moku:Pro (**FIGURE 4**). Moku:Pro is the most relevant to this topic, as it has four input/output channels and can operate at up to 5 GSa/s, but Moku:Go and Moku:Lab are ideal solutions for labs that require fewer channels or want a more portable option.

FIGURE 2: Using multiple lock-ins with external references in dual-channel SRS microscopy.[1]

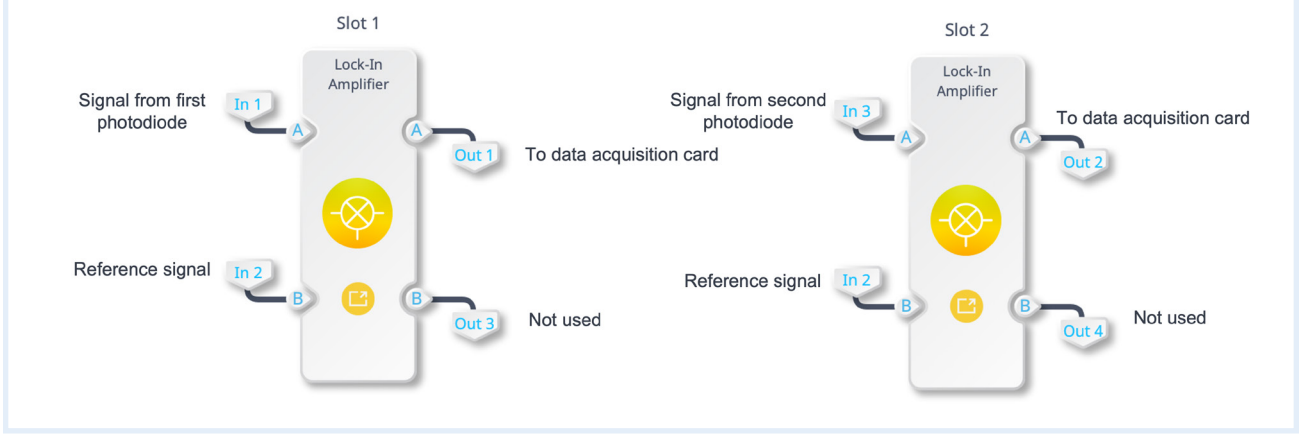
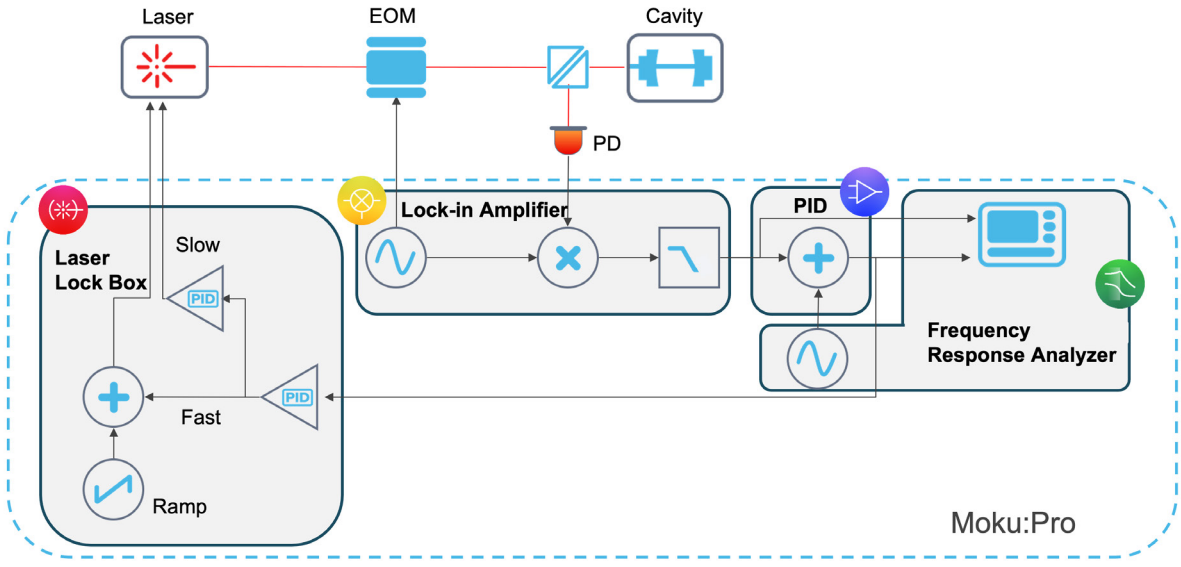


FIGURE 3: Example: PDH system for laser frequency stabilization and characterization.



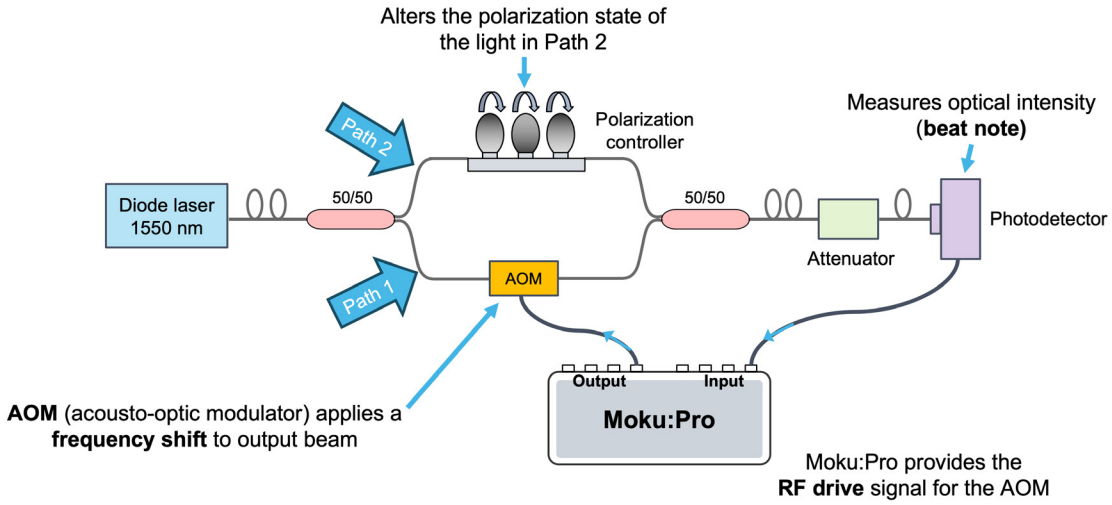
Moku equipment can run standard electronic equipment (e.g., waveform generators, arbitrary waveform generators, oscilloscopes, spectrum analyzers, data loggers), convenient tools (e.g., PID controllers, frequency response analyzers, digital filter boxes, FIR filter builders), and specialized solutions (e.g., lock-in amplifiers, phasemeters, laser lock boxes). Outside of these functions, labs can customize their devices with Moku Cloud Compile, which facilitates the deployment of custom capabilities to the FPGA.

Example: Laser Interferometer Demo

In a laser interferometer demonstration that showcased the versatility of Moku:Pro (**FIGURE 5**), it was demonstrated that none of the hardware had to be modified, as the FPGA instrument offered rapid and seamless deployment. In a Mach–Zehnder interferometer setup, the light source is split into two beams that travel different optical paths before recombining, generating interference fringes. This interference pattern can be observed to determine additional information

FIGURE 4: Moku: A family of reconfigurable devices.

FIGURE 5: Interferometer block diagram.



about the different paths, making this a powerful tool for precision measurement. Other applications for Mach–Zehnder interferometers include quantum mechanics, optical communications, and metrology.

As mentioned, the Moku:Pro device used in this demo can deploy 13 integrated instruments, and the four that were selected were the frequency response analyzer, oscilloscope, spectrum analyzer, and phasemeter. The frequency response analyzer measured the frequency of the response of the acousto-optic modulator (AOM) in magnitude and phase using a swept sine output, allowing it to identify the optimal working frequency. The oscilloscope observed the waveform of a beat note in the time domain, and the spectrum analyzer observed the waveform of a beat note in the frequency domain. The phasemeter measured in real time the frequency, phase, and amplitude for visualization of system response, and additionally logged data for post-process analysis.

There are various potential setups that can be configured on Moku devices. Scaling test setups with Multi-instrument Mode allows labs to combine multiple instruments to create a custom test system on one device, helping labs transition with the industry as it starts to focus more on tailored experiment approaches. The FPGA is divided into multiple slots in Multi-instrument Mode that can run instruments simultaneously, meaning labs can scale their hardware more seamlessly than with standard, standalone instruments.

CONCLUSION

During optical experimentation, labs are faced with many challenges, including complex setups, evolving equipment requirements, and financial and spatial constraints. The adoption of software-defined, FPGA-based test equipment offers reconfigurable systems that enhance flexibility and optimize the lab's use of time, money, and space without compromising the performance of the system. A laser interferometer demonstration using Moku:Pro serves as a tangible example of the seamless, simultaneous use of integrated instruments for better control, efficiency, and adaptability in the lab.

Reference

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