APN-005

Transient Absorption Spectroscopy (TAS)

Introduction

Transient Absorption Spectroscopy (TAS) is a powerful pump-probe technique used to study ultrafast dynamic processes in materials ranging from organic photovoltaics to biological chromophores as well as charge transfer in molecules, provided the process can be triggered directly or indirectly by a light pulse. TAS monitors changes in the optical density of a sample volume over time following excitation by a short light pulse, typically with a broadband probe pulse and with a temporal resolution limited by the duration of both. High temporal resolution is usually achieved in a scheme where excitation (pump) and probe pulse are synchronized and the delay between excitation and probe is mediated by a mechanical delay line that adjusts the optical path length for either pulse. The need for **high-repetition rate spectral detection** with **low noise and high dynamic range** makes the spectrometer a critical component of any TAS setup.

High-repetition rate CMOS-based LineScan cameras offer unique capabilities that can significantly enhance TAS measurements, particularly in terms of **throughput**, **sensitivity**, **data quality**, and **long-term stability**.

Role of Spectral Detection in TAS

In TAS, a sample is excited by a "pump" laser pulse and probed by a delayed broadband "probe" pulse generated from a common laser source. The probe light transmitted through or reflected from the sample is spectrally dispersed (typically by a monochromator, prism or grating) and captured by a detector. The change in transmission (ΔT) or absorbance (ΔA) is then calculated as a function of wavelength and time delay between pump and probe. High sensitivity is typically achieved by blocking every alternate pump pulse so that a baseline transmission or reflection spectrum is continuously updated to correct for spectral fluctuations in the broadband probe. This requires a read-out rate greater than the laser source's repetition rate. In a different detection strategy, the broadband pulse can be split into two beams where only one passes through the excited volume and the duplicate acts as a reference on a shot-to-shot basis. Additionally, pump pulse fluctuations can be monitored by a synchronized photo-diode and variations in absorbed energy corrected for. For highest sensitivity all three strategies can be implemented.

Efficient and accurate spectral detection of molecular processes requires:

- **High temporal resolution** to resolve fast processes (femtoseconds to nanoseconds)
- **Fast frame rates** for averaging and capturing low-signal events
- **High signal-to-noise ratio (SNR)** to detect subtle changes

- **High dynamic range** to accommodate both weak and strong signals
- **Spectral (wavelength-resolved) acquisition**, in single-shot or multi-shot mode

Advantages of CMOS-Based LineScan Cameras in TAS

High Repetition Rate and Frame Rate

Modern CMOS LineScan cameras can operate at tens to hundreds of kHz line rates, allowing rapid acquisition of spectral data with minimal dead time. This is well-matched with high-repetition-rate pump-probe laser systems, enabling high-throughput data collection.

Single shot Monitoring

The high speed of CMOS LineScan cameras allows capture of **every laser pulse** or **alternating pulse sequences**, enabling **shot-to-shot noise rejection, excitation correction, reference probe spectral characterization** and **real-time signal tracking**, which is critical for experiments with low signal levels or fluctuating laser sources.

Compact Form Factor and Integration

CMOS sensors are compact and easier to integrate into TAS setups. Their low power consumption and digital output interfaces simplify data handling and processing.

Multi-Region of Interest (ROI) and High Dynamic Range

Advanced CMOS cameras allow programmable ROIs and exposure control, enabling dynamic adjustment based on signal strength or specific wavelength/pixel regions. Combined with on-chip digitization, this results in improved **dynamic range and SNR.**

Application in TAS Workflows

Spectral Detection

The dispersed probe beam is imaged onto the CMOS LineScan sensor, with each pixel calibrated to a corresponding wavelength. High line rates ensure rapid acquisition, ideal for resolving transient absorption features and spectral shifts. The CMOS-based readout electronics are paired with photosensitive material corresponding to the spectral range of interest. Typically silicon-based CMOS sensors are used for detection in the visible range. InGaAs sensors are typically deployed for NIR and SWIR detection.

Change Monitoring

By synchronizing the camera to the laser system, one can systematically monitor changes in transmission, reflection or absorbance. This allows for plotting of $\Delta A(\lambda, t)$ which enables critical insight into excited-state lifetimes, energy pathways, charge transfer, and decay mechanisms like vibrational relaxation.

Observation of Transient States

Due to its high-speed capability, the camera can capture transient states that exist for only nanoseconds to femtoseconds. This has been widely applied and is particularly important for:

- Charge carrier dynamics in semiconductors
- Exciton formation and decay in organic photovoltaics
- Ultrafast light-induced energy transfer in biomolecular systems.

Synchronization and Data Acquisition

The camera's clock can be externally triggered by the laser's control system, a programmable delay generator or a light detector such as a photo-diode. Typical acquisition schemes include:

- Pump-on / pump-off cycles for differential measurements
- Real-time averaging across thousands of pulses
- Single-shot mode for unstable or single-event measurements

Advanced software frameworks can be used to control the data pipeline, applying real-time corrections such as dark subtraction, reference measurements, spectral calibration, and ΔA computation.

Conclusion

High-repetition rate CMOS-based LineScan cameras offer a powerful, flexible, and cost-effective solution for sensitive spectral detection and change monitoring in the context of transient absorption spectroscopy. Their high speed enables high temporal resolution and the integration capabilities make them well-suited for modern digital TAS setups, enabling detailed insights into ultrafast phenomena with high fidelity and throughput.