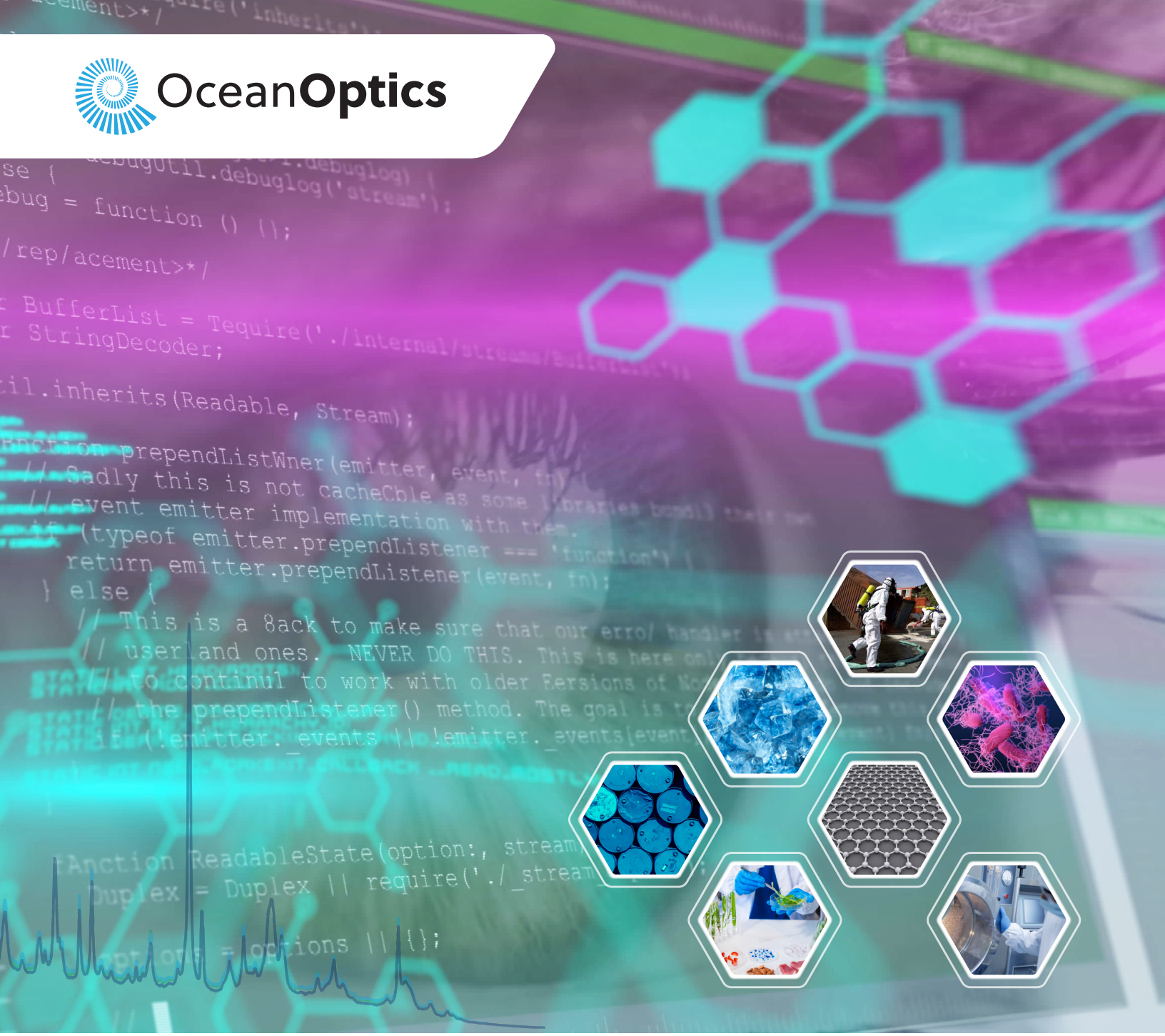
OceanOptics



Raman Application Brochure

Spectrometers | Accessories | Software | Applications

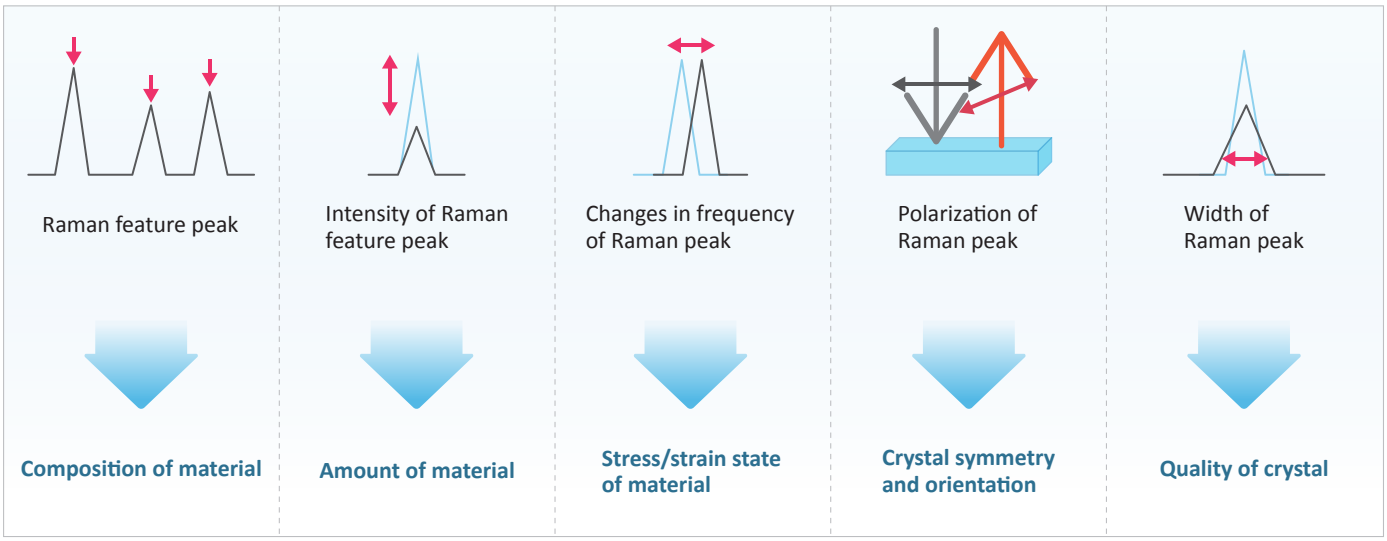
US +1 727-733-2447
EUROPE +31 26-3190500
ASIA +86 400-623-2690
info@oceanoptics.com • www.oceanoptics.com

We Measure What Matters.

What is Raman Spectroscopy?

Raman spectroscopy is an analytical technique based on the principle of Raman scattering. When a laser interacts with molecules, a tiny portion of photons exchange energy with the molecules, which changes the frequency of the scattered light. The resulting spectrum, formed by these frequency changes, provides unique information about the molecule's vibrational and rotational energy levels, much like a molecular "fingerprint". Leveraging its advantages of accuracy, speed, and non-destructive detection, Raman spectroscopy can reveal information about a substance's chemical structure, phase and morphology, crystallinity, and molecular interactions. It has become an indispensable analytical tool across materials science, chemistry, medicine, authentication, and industrial quality control.

What key information can Raman spectroscopy provide?



Advantages of Raman Spectroscopy

- No complicated sample preparation needed
- Compatible with aqueous samples, unlike FT-IR
- Rapid identification of materials via matching to spectral libraries
- Non-destructive sampling of liquids, solids, gels and surfaces
- Non-invasive measurement through bags, vials and cuvettes

Advantages of the Ocean Optics Raman Solution

Ocean Optics has been fueling the Raman revolution for 30 years, offering a diverse family of modular and turnkey systems. Designed for maximum performance in a compact, cost-effective footprint, our products let you take the power of Raman spectroscopy wherever you need to go.

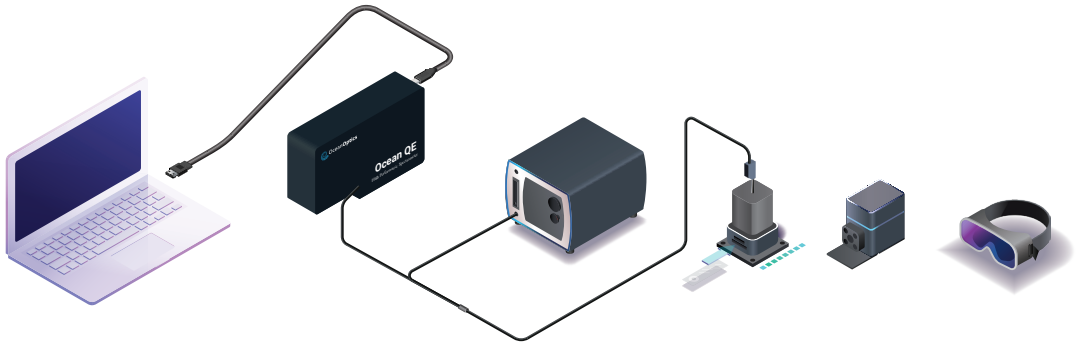
How to Build a Raman Spectroscopy System?

Building a Raman spectroscopy system is a balancing act. Signal and fluorescence background compete in selecting the excitation laser wavelength, while Raman shift range and resolution must be balanced at the detector. The application determines the needed performance and optimum laser wavelength. Whether you are a Raman expert or novice, the Ocean Optics applications team will work with you to find the best solution from our extensive line of user configurable and turnkey systems.

Modular Systems

Flexible and configurable for unique needs

Our modular products allow you to build the exact Raman system you need while maintaining the flexibility to change and optimize components as those needs evolve, including multiple lasers, probes and user-configurable spectrometers to suit almost any need. We even offer sample holders to facilitate measurement of liquids in cuvettes and vials.



Modular Systems		
Excitation Laser	532 nm, 638 nm, 785 nm, 1064 nm or Custom	
Raman Probe	Standard Probe , Dual Wavelength Probe, Process Probe	
SERS Substrates	Reproducible, stable, and robust SERS substrates for confident quantification	
Raman Sample Holder	Suitable for Raman analysis of liquids and solids	
Raman Spectrometer	 QE *Pro* Series	 NR
Features	• Configurable for diverse Raman needs • Excellent Sensitivity • Ideal for weak Raman signals	• Extremely Low Fluorescence Background • High Sensitivity in the NIR Range • Optional high-gain configuration to enhance sensitivity
Pre-configured Spectrometer	QEPRO-RAMAN-532/QEPRO-RAMAN-638 QEPRO-RAMAN-785/QEPRO-RAMAN-830	NR-RAMAN-1064
Customization	• Configurable spectral range: 200-1100 nm • User-changeable slits to optimize resolution	User-changeable slits to optimize resolution

Raman Spectrometer

The Raman spectrometer is the powerful core component of our modular system. Our spectrometers can be custom-configured based on your required excitation wavelength, resolution, range, and sensitivity. We also offer pre-configured Raman spectrometers optimized for 532 nm, 638 nm, 785 nm, or 1064 nm excitation wavelengths.

QE *Pro* High-Sensitivity Raman Spectrometer

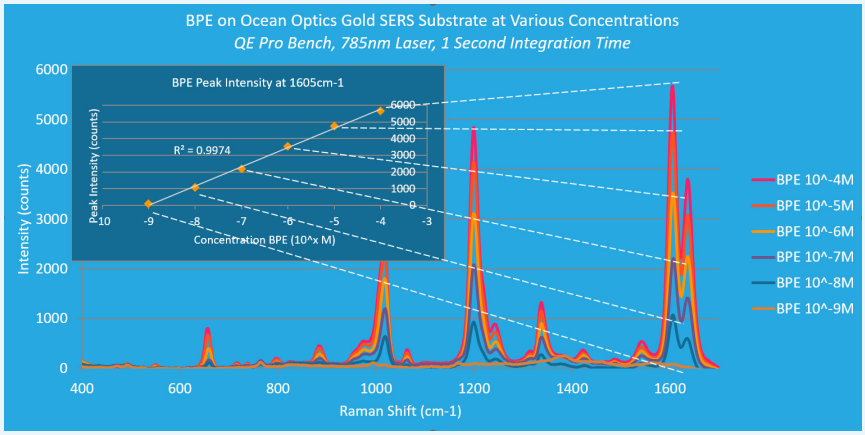
The QE *Pro* is a high-performance spectrometer featuring high sensitivity, high resolution, and an excellent signal-to-noise ratio, enabling the acquisition of high quality Raman spectra. It incorporates gold-coated mirrors and a thermoelectrically cooled (to - 40°C below ambient temperature) back-illuminated, thin-film FFT-CCD detector, resulting in minimal baseline noise even during long integration times. It can capture distinct characteristic peaks, even from very weak Raman signals. When your application requirements are not yet fully defined, the QE *Pro* is an exceptional, all-purpose tool for exploration.

NR Spectrometer

NR Series spectrometers are engineered for high performance NIR analysis, providing better SNR, dynamic range, and resolution, delivering exceptional precision and reliability. Thermoelectric cooling ensures thermal stability and consistent results, while High Gain configurations enhance sensitivity to detect even the weakest Raman signals.

Tech Tip: Raman Spectroscopy — Qualitative & Quantitative Analysis

Raman spectroscopy, renowned for its unique molecular “fingerprint” capability, is typically regarded as a qualitative method for identifying substances through their characteristic peaks. However, it can also achieve reliable quantitative analysis. The core principle is that the intensity of a molecule’s Raman scattering is directly proportional to its concentration. The most direct method is based on the intensity of a characteristic peak. Below we look at a sample of the fuel marker 1,2-di(2-pyridyl)ethylene (BPE), in various concentrations. We see the dilutions line up in perfect order with a very strong linear fit on the 1605 cm^{-1} peak intensities. For more complex samples, methods such as the internal standard method or Principal Component Analysis (PCA) are necessary to ensure the accuracy and reliability of the quantitative analysis.



Raman Accessories

To accommodate the diverse range of sample types and experimental conditions, we offer a series of optically optimized and validated accessories. You can freely select and combine them like building blocks to construct the Raman system that best suits your application.

Raman Probe

We offer high-quality, fiber-coupled Raman probes with built-in filters at the probe tip. These filters effectively eliminate excitation laser and Rayleigh scattering interference, transmitting only the Stokes Raman signal to the spectrometer. No external filtering equipment required.

Standard Raman Probe
ORP-XXX

Process Raman Probe
ORP-P785-6

Dual Wavelength Raman Probe
ORP-DW-532-785

- The ORP-Series standard Raman probes provide optical filtering of the Rayleigh line and high-signal collection in a compact, rugged design. Compatible with Ocean Optics Raman systems, these probes are suitable for laboratory, industrial and environmental applications and are available for several excitation wavelengths.
- The Process Raman Probe is built for rugged applications, with a sealed, swageable lens shaft suitable for immersion, pressure, and vacuum conditions. Probes incorporate backscattering optics for high collection efficiency and are compatible with a wide range of sample types including solids, liquids, and gases.
- Our Dual Wavelength Raman Probe features a colinear optical design and high-throughput optics for efficient, simultaneous measurements at 532/785 nm—ideal for complex sample interrogation.

	Standard Raman Probe	Process Raman Probe	Dual Wavelength Raman Probe
Excitation Wavelength	532/638/785/830/1064 nm	785 nm, Other Wavelengths available	532/785 nm
Spectral Range	100-4000 cm^{-1} (range is spectrometer dependent)		
Focal Length	9 mm standard (12, 15 & 18 mm optional) Note: Probe efficiency decreases with increasing focal length		
Spot Diameter at the Sample	100 µm for 100 µm excitation fiber (fiber core dependent)		
Operating Temperature	0-85°C	0-325°C	0-85°C (non-immersion shaft), 0-325°C (sealed shaft)
Operating Pressure	15 psi	6000 psi	15 psi (non-immersion shaft), 6000 psi (sealed shaft)

Lens Barrels

Specifications	ORP-LWD-47	ORP-LB-6 (Industrial)	ORP-SWD-LB
	 **Non-Contact Long Working Distance Lens Barrel**	 **Compression Seal Immersion Lens Barrels**	 **Short Working Distance Sealed Lens Barrel**
Barrel Material	316 stainless steel	316 stainless steel (Other metals such as Hastelloy, Inconel, Monel, or Titanium available)	
Focusing Lens Working Distance	47mm Note:20 to 100 mm available	5mm	< 0.5mm
Dimensions	1” diameter, 3.9” length	3/8” diameter, 6” long	3/8” diameter, 6” long
O-ring Seal	NA	Teflon Note: Kalrez® O-ring available	Kalrez® O-ring Note: Teflon, Gold available
Numerical Aperture	0.20	NA	NA
Operating Temperature	0 to 125°C	-40°C to 350°C	-40°C to 250°C
Maximum Operating Pressure	15 psi	Ambient to>3000 psi	>3000 psi
Window	NA	Sapphire (Fused silica available)	Sapphire

Excitation Lasers

A laser with excellent stability and spectral purity yields a clean, high quality Raman spectrum. Our multimode 532 nm, 638 nm, 785 nm and 1064 nm excitation lasers use innovative stabilization and thermoelectric cooling to lock wavelength, making them as reliable as they are easy to use. Their high power, narrow linewidth and side mode suppression of greater than 40 dB results in extremely high signal-to noise ratio Raman spectra.

Tech Tip: Choosing Raman Excitation Wavelength

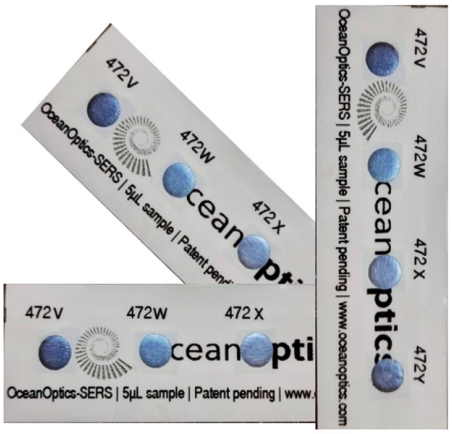
Theory predicts that Raman signal intensity will scale as $(1/\lambda^4)$, where λ is the wavelength of the excitation laser. While shorter wavelengths generate a stronger Raman signal, they can also induce autofluorescence, particularly in organic materials. Appearing as a broad background, autofluorescence signal can overwhelm the Raman spectrum, or at the very least degrade signal to noise and make Raman peaks difficult to resolve.

- Organic substances are particularly prone to fluorescence, so red or near-infrared (NIR) lasers (typically 660-830 nm) are generally used for excitation.
- Inorganic materials exhibit much less fluorescence interference. For samples like carbon nanotubes and C60, 532 nm excitation laser is commonly used.
- When using 1064 nm laser, fluorescence interference is virtually eliminated. Measurements in this spectral range can be performed with our NR Spectrometer.

Surface Enhanced Raman Scattering

Surface Enhanced Raman Spectroscopy (SERS) is a powerful sensing tool that amplifies weak Raman signals from molecules. In SERS, analytes are adsorbed onto a three-dimensional particle surface prior to analysis. This interaction induces a plasmon resonance effect that can boost Raman signal intensity by millions of times.

Our high-performance substrates feature a unique, patented SIGNAL ENHANCING HEAT SINK technology. Each slide includes four large active SERS chips with clear serialization. These chips are especially sensitive, enabling trace-level detection of samples such as explosives and pesticides.

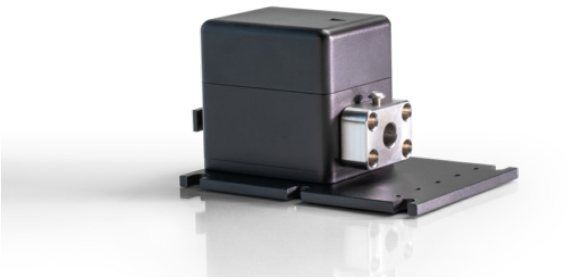


Parameter	Units	Specification
Substrate Dimensions	mm	75 x 24 x 0.2
Active Area (free chip size)	mm	6
Number of Active Areas (chips)	-	4
Analyte Volume	µL	5 - 10
Substrate Surface	-	Polyethylene flexible adhesive film
Raman Laser Excitation Wavelength Range	nm	671 / 785 / 830/ 1064
Shelf Life for Optimum Performance	months	8
Long Term Storage Temperature	°C (°F)	5 - 60 (40 - 140)
Long Term Storage Humidity	% RH	< 50, non condensing

Other Accessories

Raman Probe Sample Holders

We offer sample holders for Raman analysis of liquids and solids. The holders accommodate Raman probes from 9.5 mm-12.7 mm diameter, and 1 cm pathlength cuvettes and vials of various dimensions.



Laser Safety Glasses

Raman laser safety glasses offer great protection from laser light without sacrificing visibility or comfort. The glasses are designed for both direct and diffuse viewing and are EN207-compliant and CE-certified.

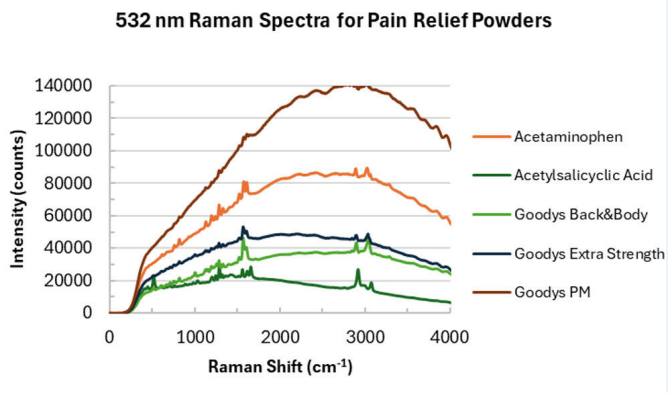
Raman Software

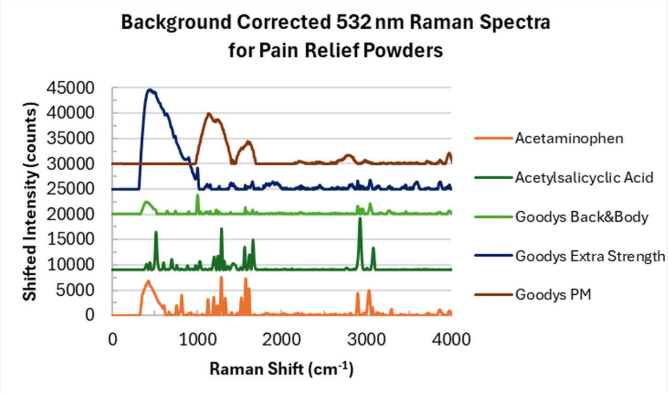
OceanView 2.0 is our powerful, signature desktop spectroscopy application. The software has a clean graphical interface and provides fast, stable data acquisition and processing. The enhanced OceanView 2.0 GUI also has easily identifiable icons and better visual contrast to reduce eyestrain. Other changes compared to earlier versions include boosted software functionality for a more robust, streamlined experience.

System Requirements	
Communication Buses	USB, RS232, Ethernet
HD Space	300 MB free space
Monitor Resolution	1024 X 768 or higher
Operating Systems	Windows 7/8.x/10, MacOS X 10.7.3, Linux 32/64
Processor	Intel Core II Duo @ 1.4 GHz or better Intel Core Duo @ 2.0 GHz or better AMD Athlon Neo X2 @ 1.6 GHz or better Intel Atom @ 2.13 GHz or better AMD Athlon 64 x2 @ 1.7 GHz or better
RAM	1.5 GB or higher
Library	No Library included

Tech Tip: How to Remove Fluorescence Background Interference?

The OceanView Clean Peaks feature effectively eliminates fluorescence background for superior baseline correction. This delivers cleaner, sharper Raman peaks, enabling more accurate and reliable spectral analysis.





Typical Fields of Raman Application

Biomedical & Pharmaceutical

- Bacterial Detection in Pharmaceuticals
- Raw Material Identification
- Detection of Illicit Adulterants in Traditional Chinese (TCM) and Western Medicine
- Cancer Detection

Food Safety

- Adulteration and Authenticity
- Pesticide Residue Detection
- Detection of Prohibited Additives (e.g., Malachite Green)

Security & Forensics

- Rapid Identification of Narcotics or Illicit Drugs
- Explosives Detection
- Trace Evidence Analysis

Gemology & Archaeology

- Gemstone Identification
- Mineral Composition and Structural Analysis
- Cultural Heritage Restoration and Authentication

Materials Science

- Material Structure Identification
- Polymer Detection and Characterization

Environmental

- Water Quality Analysis
- Air Pollution Analysis

Industrial Monitoring

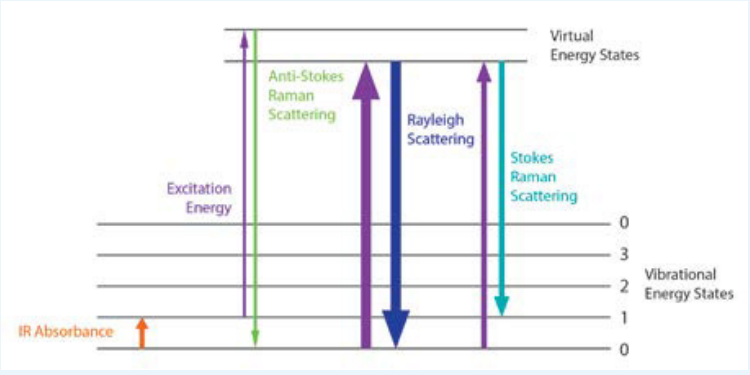
- Bioprocess Monitoring
- Epoxy Resin Curing Process Monitoring

Tech Tip: Calculate Raman shift

As excitation photons interact with sample molecules, energy transfer may occur. This energy transfer alters the photon's frequency. The frequency difference between the scattered and incident light is called the Raman shift.

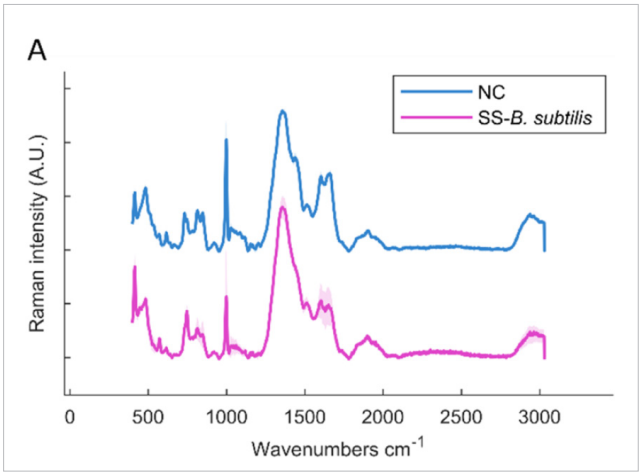
The following equation is used to calculate the Raman shift (Δν), expressed in wavenumbers (cm^{-1}) , from the laser wavelength (λ_0) and the Raman peak wavelength (λ_x):

$$\Delta\nu_x(cm^{-1}) = \left(\frac{1}{\lambda_0(nm)} - \frac{1}{\lambda_x(nm)}\right) \times \left(\frac{10^7\,(nm)}{cm}\right)$$



Detection of Bacterial Cells in a Pharmaceutical Drug Product

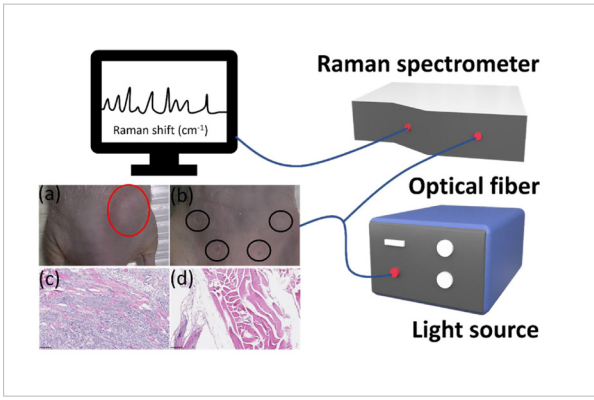
This study utilized an Ocean Optics QE *Pro* 785 nm Raman spectrometer, achieving high-sensitivity detection of bacteria (including spores) at concentrations as low as 10 CFU/mL within the drug's original, unopened packaging[1]. This rapid and cost-effective method shows significant potential for quality control in the pharmaceutical industry.



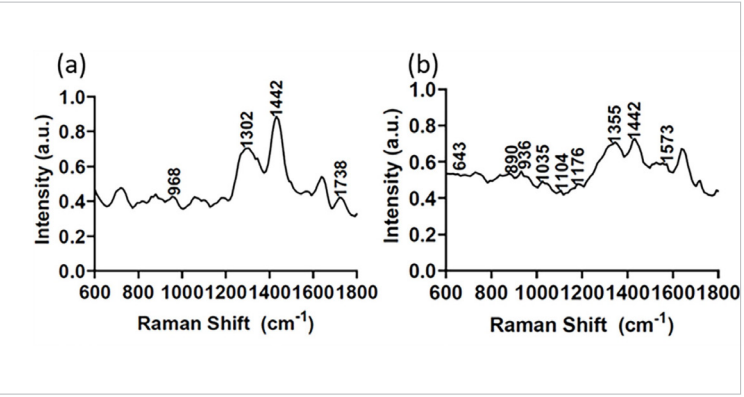
This figure compares the Raman spectra of a sterile sample (NC) and a bacteria-contaminated sample (SS-vBS). Both groups presented similar spectra but with small variations in the intensity of peaks related to bacterial-associated organic molecules observed in the wavenumber ranges 700-1800 and 2800-3200 cm^{-1} (Key spectral features include nucleic acid signals at 786 and 1090 cm^{-1} and the Amide I vibration at 1656 cm^{-1}). These differences reflect the characteristic vibrations of bacterial biomolecules, providing direct evidence that Raman spectroscopy can specifically identify bacterial signals from a complex pharmaceutical matrix.

Detection of Breast Cancer

Accurate discrimination between late-stage breast cancer tissue and normal breast tissue in mice was achieved using an Ocean Optics QE *Pro* 785 nm Raman spectrometer combined with machine learning algorithms [2]. This provides a novel, rapid and non-destructive method for the detection of breast cancer, offering promising applications in intraoperative settings.



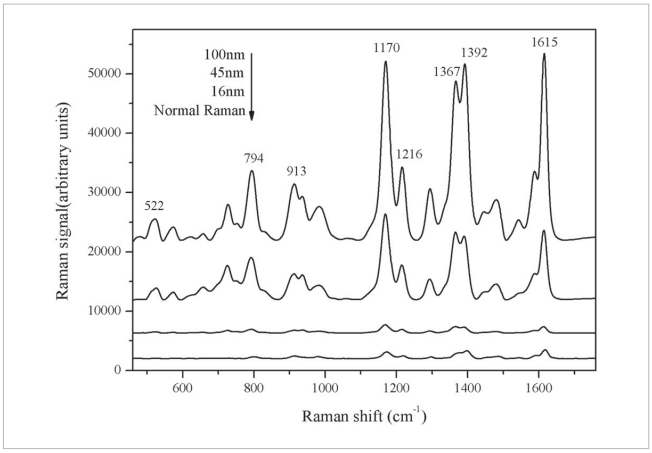
Schematic diagram of Raman system in a murine cancer model. (a) tumor; (b) normal breast; (c) tumor with H&E staining; (d) normal breast with H&E staining



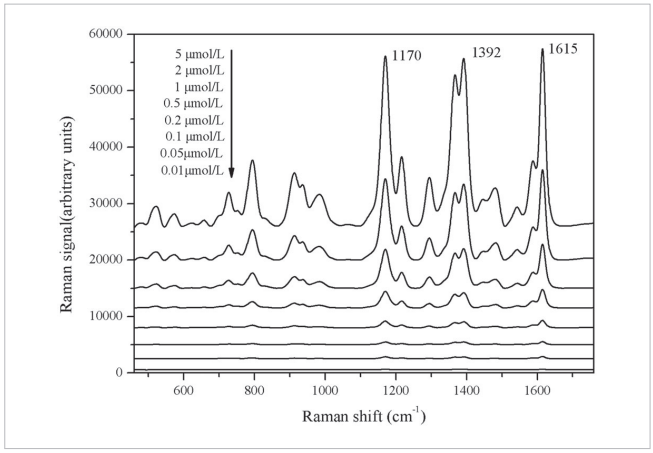
This figure shows the normalized average Raman spectra of healthy (a) and cancerous mammary tissues (b). The pronounced lipid content (e.g., 968, 1442, and 1738 cm^{-1}) exists in the healthy mammary tissue (a); conversely, the cancerous tissue shows an elevated intensity of proteins (e.g., 890 cm^{-1} and 1104 cm^{-1}) and decreased 1442 cm^{-1} band owing to the contribution of lipids. The increased protein content and altered lipid profiles in cancerous tissues indicate the metabolic reprogramming associated with cancer progression.

Detection of Malachite Green in Aquaculture with SERS

This case study demonstrates a superior solution that uses an Ocean Optics QE *Pro* 785 nm Raman spectrometer with SERS technology and a data analysis model to achieve rapid, highly sensitive detection of trace Malachite Green in aquaculture water [3]. This method is ideal for on-site screening and real-time monitoring, offering a powerful tool to ensure the safety of seafood.



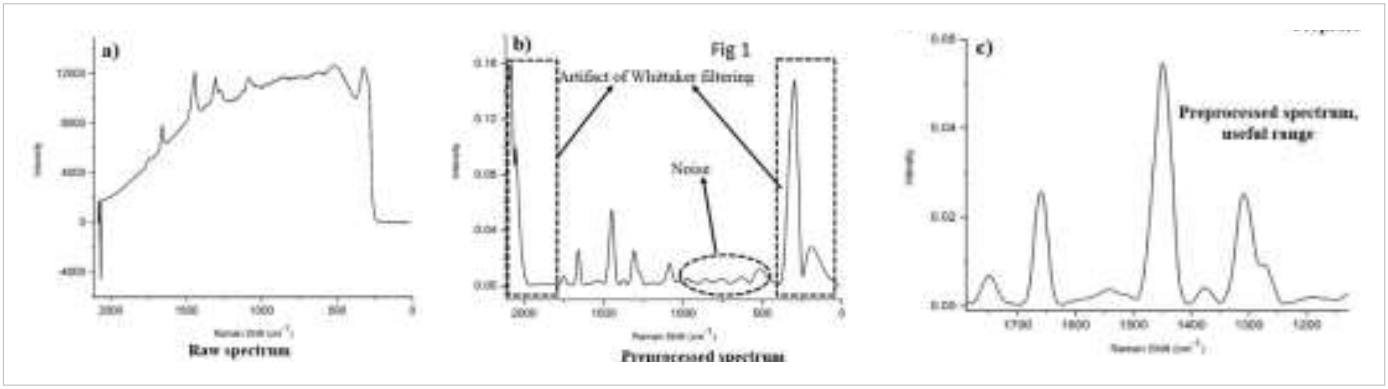
The figure shows SERS spectra of 5.0 μmol·L^{-1} malachite green on 16, 45, and 100 nm gold nanoparticles and normal Raman spectrum of 0.5 mol·L^{-1} malachite green. The spectra indicate that the SERS signal is significantly enhanced with 100 nm gold particles, and the peaks of malachite green (such as the one at 1615 cm^{-1}) are clearly distinguishable.



The figure shows SERS spectra of malachite green standard solution with different concentrations from 0.01 μmol·L^{-1} to 5.0 μmol·L^{-1} adsorbed on 100 nm gold nanoparticles. As the concentration decreases, the signal intensity weakens but remains recognizable, demonstrating that the method has reliable quantitative capabilities over a wide concentration range.

Differentiation of Edible Oils

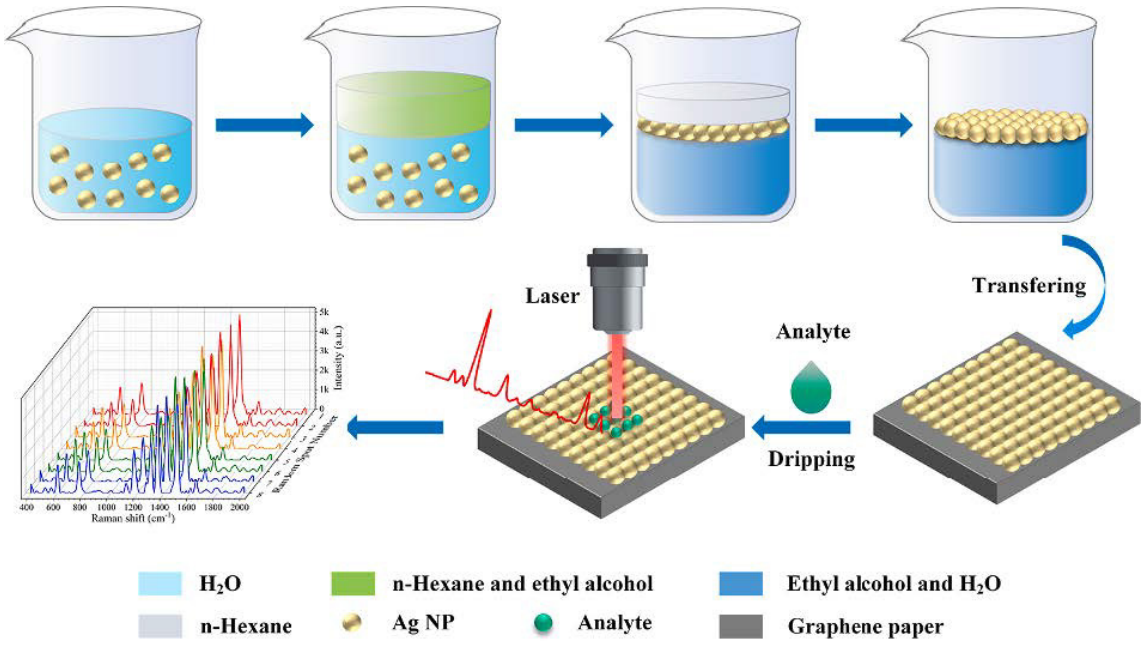
Raman spectroscopy offers a fast, non-destructive way to analyze edible oils without the need for complex sample pretreatment. This case study utilized Ocean Optics QE65000 (now upgraded to the QE *Pro*) 785 nm Raman spectrometer, combined with data analysis, to successfully differentiate and identify common types of edible oil[4]. This provides an efficient and reliable on-site detection method for oil identification and adulteration screening.



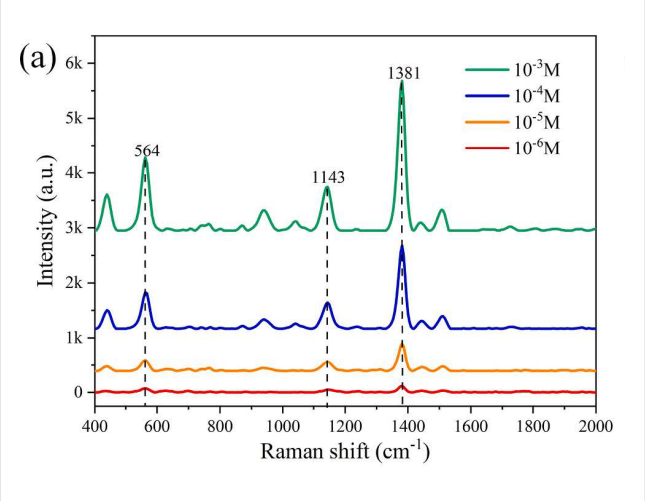
The figure shows the Raman spectrum of corn oil. The original spectrum (a) is treated to remove the fluorescent background and process the signal, resulting in a distinct characteristic signal (c). These feature peaks directly reflect the molecular structural differences of edible oils, enabling accurate discrimination of different oil types.

Detection of Pesticide Residue with SERS

Surface-enhanced Raman scattering (SERS) is a highly sensitive spectroscopic technique that excels at trace level analyte detection. In this case study, a novel flexible SERS substrate based on silver nanoparticles/graphene paper was developed. Using an Ocean Optics QE *Pro* 785 nm Raman spectrometer, this study achieved the accurate identification and quantitative analysis of the pesticide residue thiram in orange juice[5]. This highlights the practical value of Raman spectroscopy for pesticide residue screening.



Schematic of the preparation and detection process for the Ag NPs/GP SERS substrate.



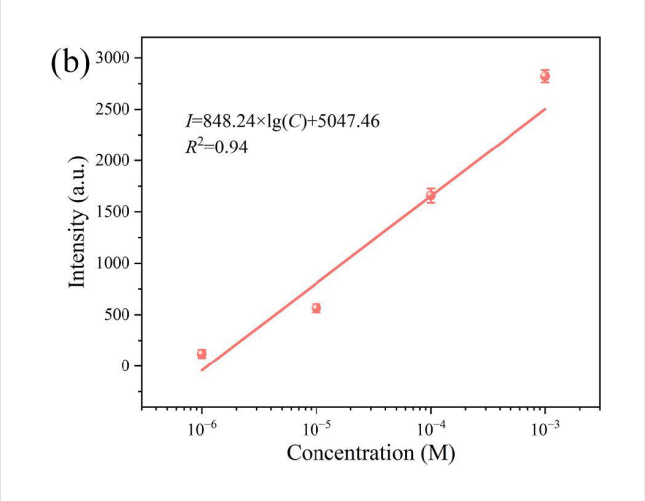
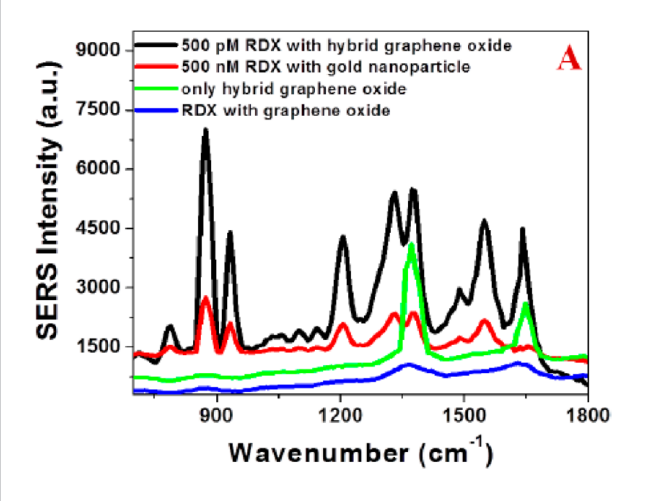


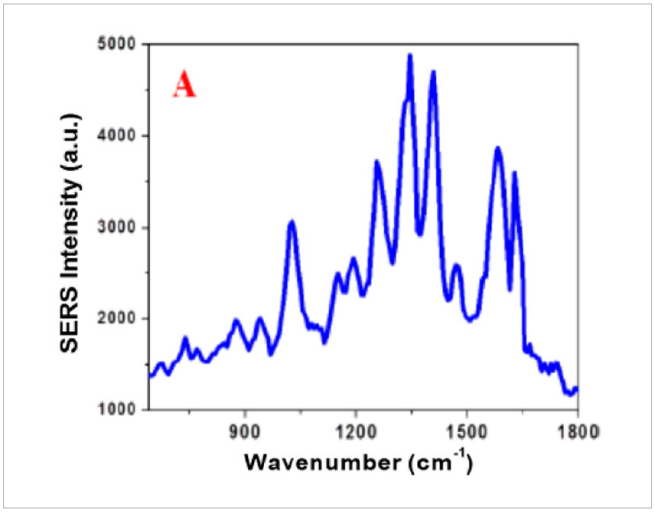
Figure (a) shows the SERS spectra of thiram at different concentrations. Multiple Raman characteristic peaks of thiram (such as the C-N stretching and CH_3 deformation vibrations at 1381 cm^{-1}) are observed. As the concentration of thiram decreases, the intensity of the Raman characteristic peaks gradually weakens, indicating that this SERS technique can effectively detect thiram at low concentrations.
Figure (b) illustrates the linear relationship between the intensity of the characteristic peak at 1381 cm^{-1} and the concentration of thiram on the SERS substrate. This demonstrates the high sensitivity of this SERS-based method for the quantitative analysis of thiram.

Identification of Explosives with SERS

Trace level identification of explosive molecules is very important not only for security screening but also for the environment and human health. This case study developed a gold nanocage–graphene oxide hybrid platform, using an Ocean Optics QE 65000 (now upgraded to the QE *Pro*) 670 nm Raman spectrometer, and achieved ultra-sensitive, label-free detection of the nitro-explosives RDX and TNT, with a limit of detection (LOD) down to the femtomolar level[6]. Compared to laboratory Raman systems, this modular Raman systems offers faster and more convenient detection, making it ideal for reliable on-site identification of explosives



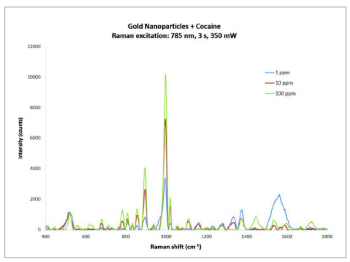
At a concentration as low as 500 pM, the key Raman feature peak of RDX (such as the symmetric ring-breathing vibration at 870 cm^{-1}) remains clearly visible on the gold nanocage-graphene oxide hybrid SERS platform.



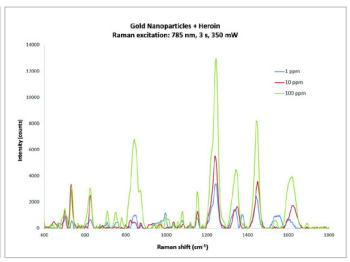
At a concentration as low as 800 fM, the NO_2 symmetric stretching vibration band of TNT at 1360 cm^{-1} is clearly observed on the gold nanocage-graphene oxide hybrid SERS platform.

Rapid Testing for Illicit Drugs with SERS

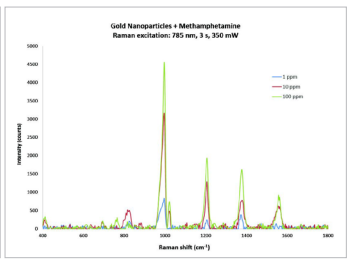
Surface Enhanced Raman Spectroscopy (SERS) is a powerful sensing tool that amplifies weak Raman signals from molecules, allowing for the fast and precise detection of trace levels of illicit drugs. Using an Ocean Optics QE *Pro* 785 nm Raman spectrometer with a gold nanoparticle SERS substrate, we successfully detected illegal substances including cocaine, heroin, methamphetamine, and THC down to the ppm level. This method not only avoids fluorescence interference but also significantly improves the limit of detection (LOD), making it suitable for on-site rapid screening scenarios in security checks and anti-drug operations.



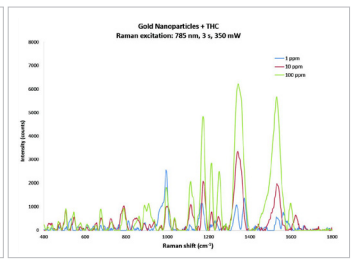
The enhanced Raman spectrum of cocaine



The enhanced Raman spectrum of heroin reveals distinct spectral features.



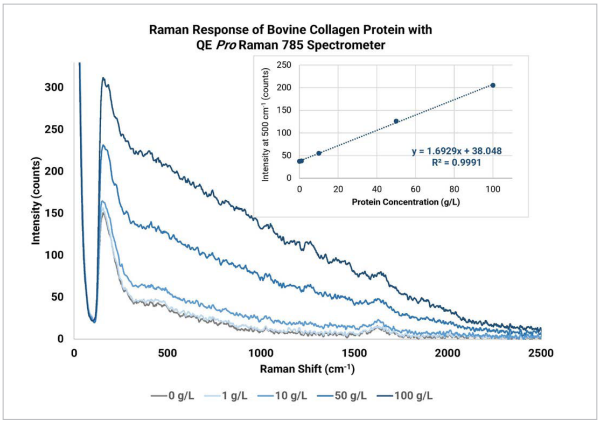
The enhanced Raman spectrum of methamphetamine shows a strong peak near 1000 cm^{-1}



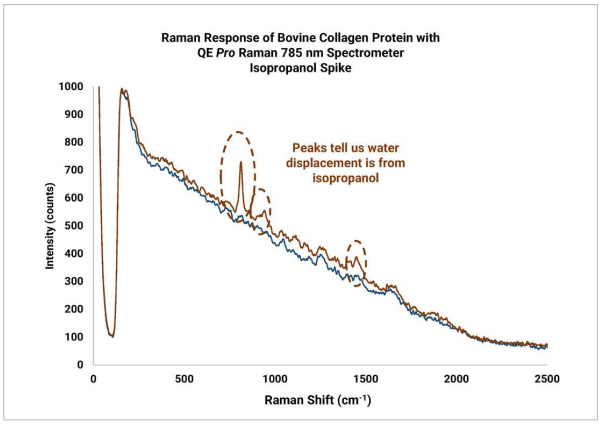
Strong Raman response is observed for THC despite the potential for interference from fluorescence

Bioprocess Monitoring

In biopharmaceutical processes, monitoring both proteins and small organic molecules is critical. While traditional UV-Vis spectroscopy accurately measures protein levels, it cannot identify small molecules. In this case study, an Ocean Optics QE *Pro* 785 nm portable Raman system was successfully utilized to detect trace amounts of compounds like isopropanol through their unique molecular fingerprint. This Raman approach provides reliable verification for both protein concentration and organic molecule identification, creating a solid foundation for process optimization.



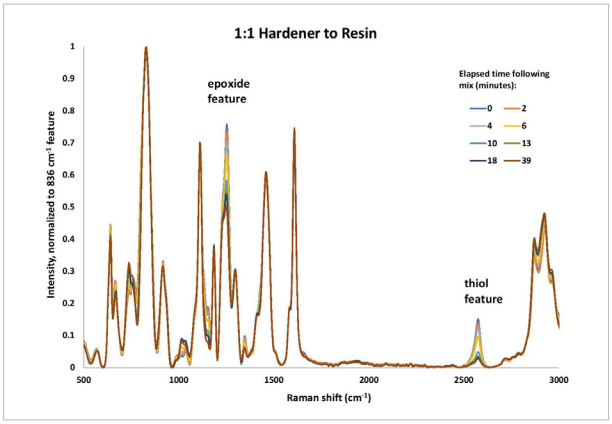
The figure shows the Raman response of bovine collagen protein. Although this approach is inherently less sensitive to concentration than the UV-Vis method, its spectral features can still reflect the trend in protein concentration changes, allowing for cross-validation of the UV-Vis measurement results.



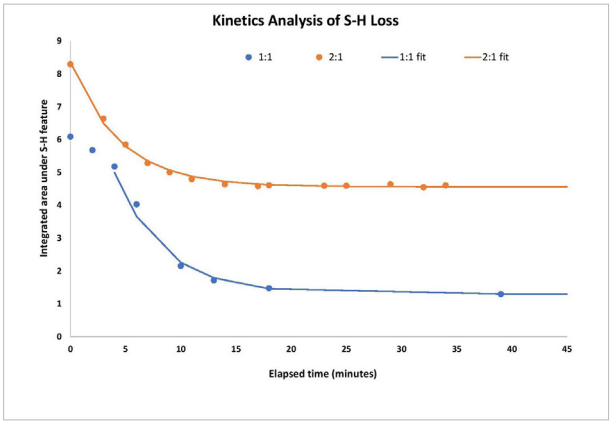
The figure shows the Raman response of bovine collagen protein after spiking with isopropanol. The characteristic peaks of isopropanol appear in the range of approximately 800–1200 cm^{-1}, indicating the presence of this organic compound in the system.

Epoxy Resin Curing Reaction Monitoring

Raman spectroscopy is ideal for monitoring chemical reactions because it is non-destructive, highly specific, and works in real-time. This case used an Ocean Optics QE *Pro* 785 nm spectrometer to monitor epoxy resin curing by tracking the intensity changes of epoxy and thiol fingerprint peaks. This method provides immediate, in-situ data on reaction progress and the degree of cure, making it a reliable tool for industrial process control and material analysis.



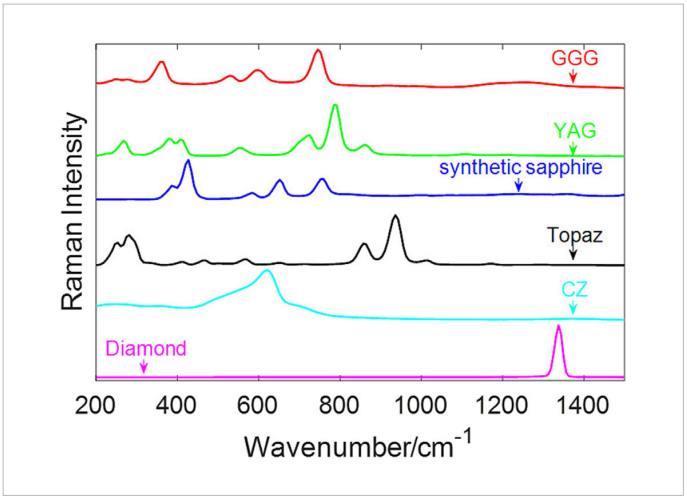
The Raman spectra of the curing process for 1:1 ratio of hardener to epoxy resin. The change of the 1254 cm^{-1} feature peak with time can be interpreted as the consumption of the free epoxide groups, while the decrease at 2575 cm^{-1} reflects the consumption of thiol (-SH) in the hardener as the material reacts.



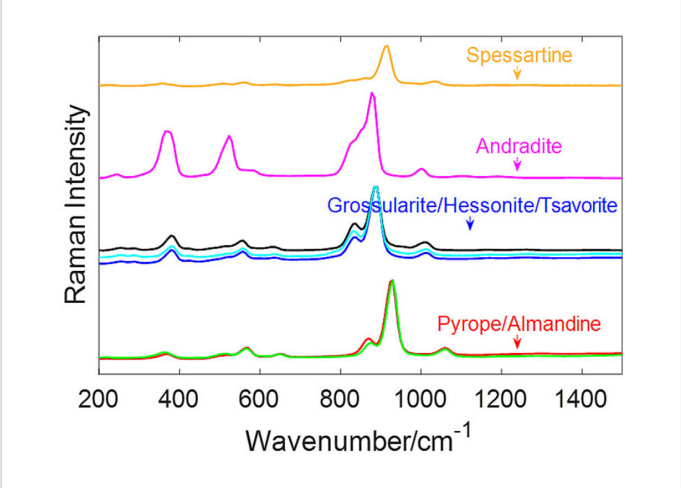
A kinetic analysis performed on the 1:1 and 2:1 hardener-to-resin samples based on the -SH feature peak. The results demonstrate that while the main reaction stage exhibits similar kinetic characteristics for both formulations, the 2:1 system shows that more unreacted-SH remains when more hardener has been added.

Gemstone Identification

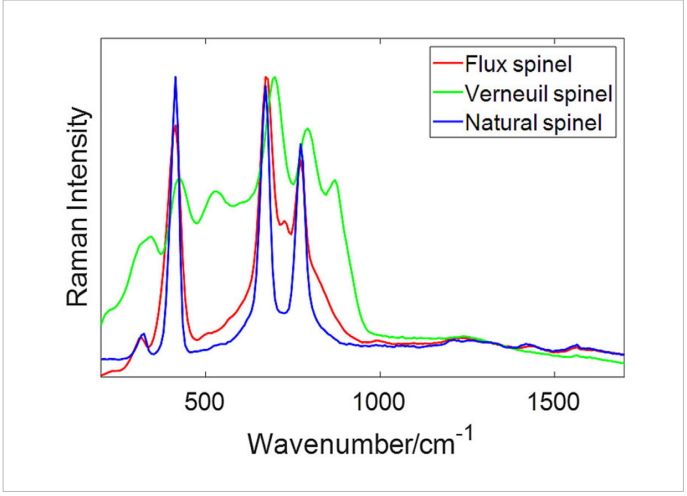
Raman spectroscopy is widely used in the field of gemstone identification due to its key characteristics of being non-destructive, rapid, and requiring no sample preparation. In this case study, an Ocean Optics QE *Pro* 405 nm portable Raman system was successfully utilized to identify the mineral composition of 57 common gemstones[7]. Furthermore, it could distinguish between natural and synthetic stones, providing an efficient and low-cost tool for jewelry analysis.



This figure shows typical Raman spectra for diamond and commonly encountered diamond simulants. The feature peak of diamond at 1332 cm^{-1} allows for the rapid differentiation between real diamonds and simulants.



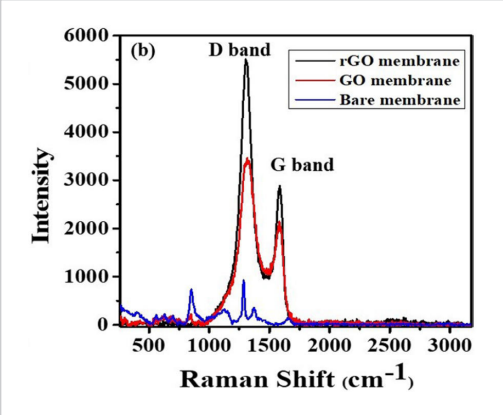
This figure shows Raman spectra of different types of garnets. Differences in the characteristic Raman peaks allow for the clear distinction between various garnet varieties.



This figure shows Raman spectra of natural and synthetic spinels. Based on differences in feature peak positions, peak shapes, and background signals, it is allowed to distinguish between natural spinel, verneuil spinel, and flux spinel, providing a basis for the identification of synthetic gemstones.

Characterization of Structural Defects in Carbon Nanomaterials

Raman spectroscopy is extremely sensitive to structural defects and chemical bonding variations in carbon materials, enabling it to effectively distinguish between graphene oxide (GO) and reduced graphene oxide (rGO). The intensity ratio of the D peak to the G peak (I_D/I_G) is particularly useful for evaluating defect density and the degree of graphitization. This case study utilized Raman spectroscopy to characterize the structural defects and reduction level of GO and rGO membranes, successfully demonstrating that the reduction process increased surface defects in the rGO membrane[8]. This provides a crucial structural foundation for optimizing membrane performance.



The figure shows the Raman spectra of GO, rGO, and bare membrane. As can be clearly seen, the I_D/I_G ratio for rGO (1.9) is significantly higher than that for GO (1.6). This is direct evidence that more structural defects were introduced to the material surface during the reduction process. This microstructural change is the underlying reason for the enhanced water flux of the rGO membrane, perfectly demonstrating the core role of Raman spectroscopy in linking a material's microstructure to its macroscopic application performance.

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Manufacturing & Logistics
3500 Quadrangle Blvd.,Orlando, FL 32817,USA

Sales: info@oceanoptics.com
Orders: orders@oceanoptics.com
Support: support@oceanoptics.com

Phone: +1 727-733-2447
Fax: +1 727-733-3962