SFG Spectrometers

Sum Frequency Generation Vibrational Spectroscopy

Sensitive and selective to the orientation of molecules in the surface layer

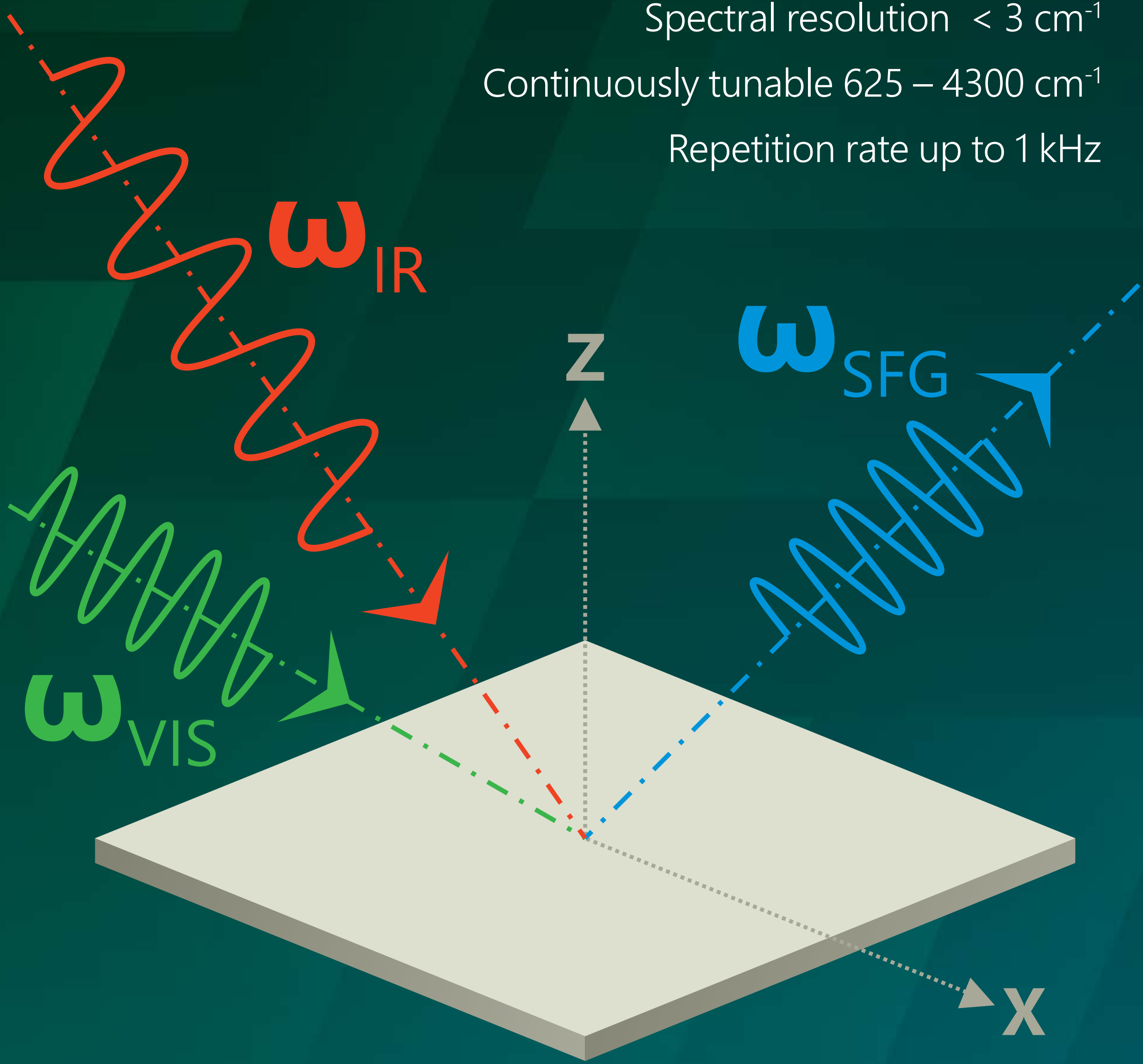
Picosecond scanning

Femtosecond broadband

Spectral resolution < 3 cm^{-1}

Continuously tunable 625 – 4300 cm^{-1}

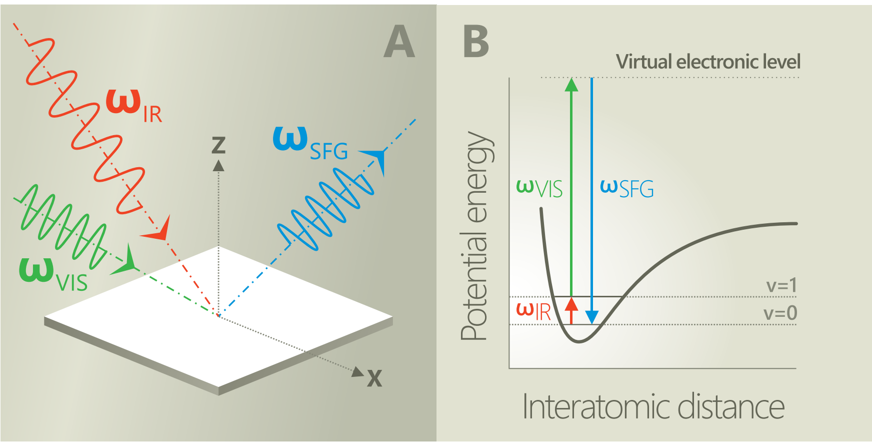
Repetition rate up to 1 kHz



Sum Frequency Generation Vibrational Spectroscopy

Sum Frequency Generation Vibrational Spectroscopy (SFG-VS) is powerful and versatile method for in-situ investigation of surfaces and interfaces. In SFG-VS experiment a pulsed tunable infrared IR (ω_{IR}) laser beam is mixed with a visible VIS (ω_{VIS}) beam to produce an output at the sum frequency ($\omega_{SFG} = \omega_{IR} + \omega_{VIS}$). SFG is second order nonlinear process, which is allowed only in media without inversion symmetry. At surfaces or interfaces inversion symmetry is necessarily broken, that makes SFG highly surface specific. As the IR wavelength is scanned, active vibrational modes of molecules at the interface give a resonant contribution to SF signal. The resonant enhancement provides spectral information on surface characteristic vibrational transitions.

Vibrational sum frequency generation (SFG) spectroscopy offers several important advantages over traditional spectroscopy methods for the molecular level analysis of interfaces, including surface sensitivity, vibrational specificity, and the possibility to extract detailed information on the ordering and orientation of molecular groups at the interface by analysis of polarization-dependent SFG spectra.



SFG signal generation diagram (a) and the molecular energy level diagram for the SFG process (b)

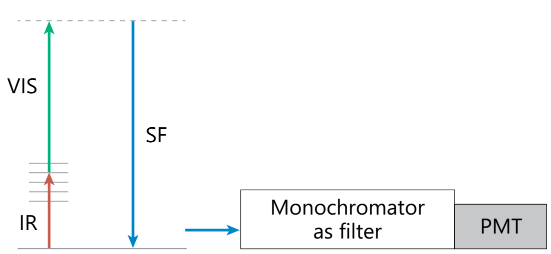
ADVANTAGES

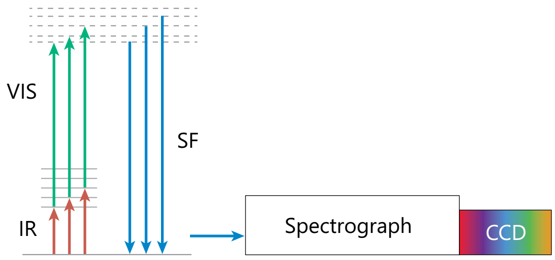
- *Sensitive and selective to the orientation of molecules in the surface layer*
- *Intrinsically surface specific*
- *Selective to adsorbed species*
- *Sensitive to submonolayer of molecules*
- *Applicable to all interfaces accessible to light*
- *Nondestructive*
- *Capable of high spectral and spatial resolution*

APPLICATIONS

- *Investigation of surfaces and interfaces of solids, liquids, polymers, biological membranes and other systems*
- *Studies of surface structure, chemical composition and molecular orientation*
- *Remote sensing in hostile environment*
- *Investigation of surface reactions under real atmosphere, catalysis, surface dynamics*
- *Studies of epitaxial growth, electrochemistry, material and environmental problems*

Narrowband picosecond scanning and broadband femtosecond SFG spectrometer





Narrowband picosecond scanning SFG spectrometer

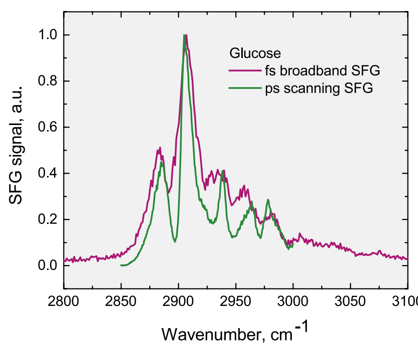
In order to obtain SFG spectrum during measurement wavelength of narrowband mid-IR pulse is changed point-by-point throughout the range of interest. Narrowband SFG signal is recorded by the time-gated photomultiplier. Energy of each mid-IR, VIS and SFG pulse is measured. After the measurement, the SFG spectrum can be normalised according to IR and VIS energy. Spectral resolution is determined by the bandwidth of the mid-IR light source. The narrower mid-IR pulse bandwidth, the better the SFG spectral resolution. Separate vibrational modes are excited during the measurement.

Broadband femtosecond SFG spectrometer

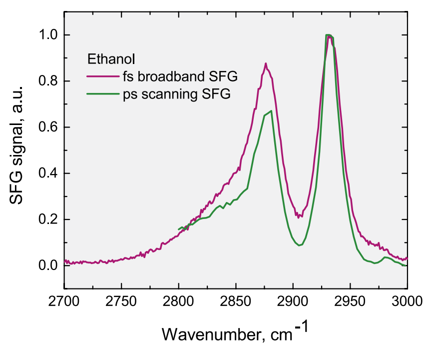
A broadband mid-IR pulse is mixed with a narrowband VIS pulse. The result is broadband SFG spectrum which is recorded using a monochromator and a sensitive CCD camera. The full spectrum is acquired simultaneously by integrating signal over time. Spectral resolution is determined by the bandwidth of the VIS pulse and the spectrograph resolution. The narrower the bandwidth of VIS pulse, the better the SFG spectral resolution.

COMPARISON OF DIFFERENT SFG SPECTROMETERS

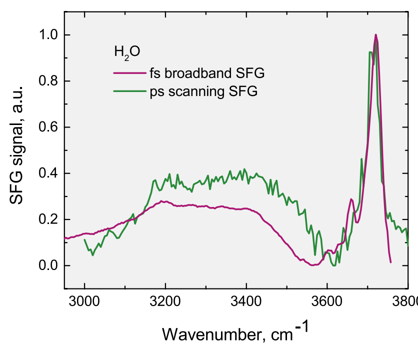
Narrowband picosecond scanning spectrometer	Broadband femtosecond high resolution spectrometer
Narrowband mid-IR excitation, only one band is excited. Coupled states can be separated.	Simultaneous excitation and recording of broad vibration spectrum with high resolution.
High mid-IR pulse energy. Less influence of IR absorbtion in the air.	High mid-IR intensity at low pulse energy – suitable for biological or other water containing samples.
No reference spectrum needed, IR energy measured at each spectral point.	Optically coupled IR and VIS channels. Reduced complexity and increased stability of the system.



SFG spectra of glucose



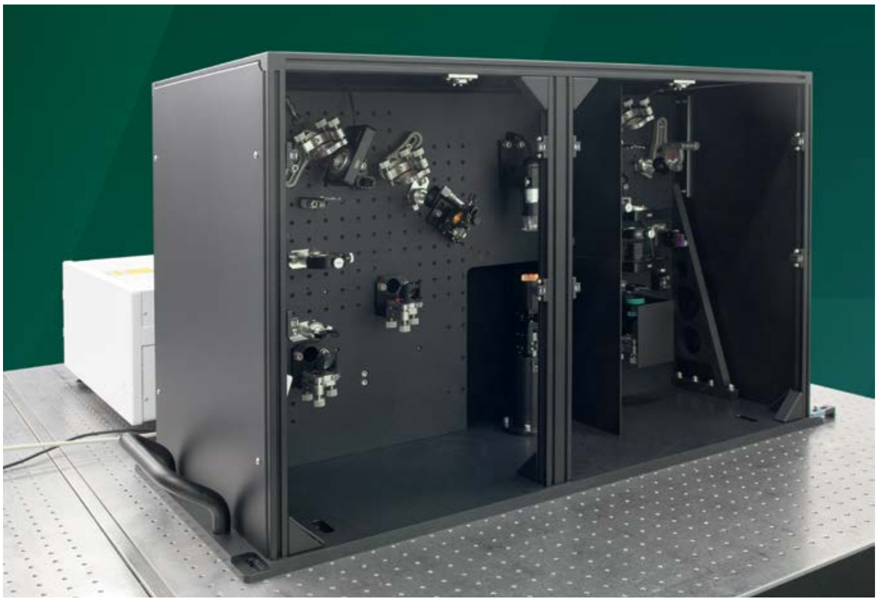
SFG spectra of ethanol



SFG spectra of water

Spectra are different because of different water samples. Water spectrum strongly depends on purity of the water.

Features and design of the picosecond scanning SFG spectrometer



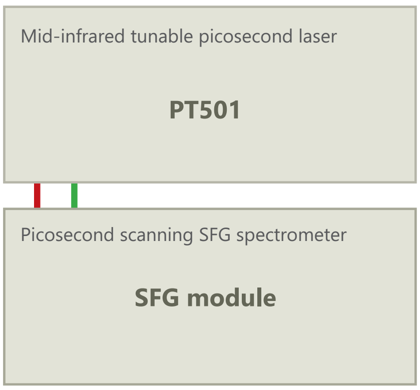
SYSTEM COMPONENTS

- *Picosecond mode-locked Nd:YAG laser and optical parametric generator in one unit*
- *Spectroscopy module with:*
  - *– PMT based signal detectors*
  - *– Data acquisition system*
  - *– Dedicated LabView® software package for system control*

NEW FEATURE

- *Fast wavelength scan (sweep)*

The SFG spectrometer developed by Ekspla engineers is a nonlinear spectrometry instrument, convenient for everyday use. Ekspla manufactures SFG spectrometers, which are used by chemists, biologists, material scientists, and physicists. The spectrometer has many features that help to set up measurements and to make successful vibrational spectroscopy studies. For chemical and biochemical laboratories, this makes the Ekspla SFG spectrometer a reliable workhorse with a broad spectral region, automatically tuned from 625 to 4300 cm^{-1}, a high spectral resolution (3 cm^{-1}), and easily controlled adjustment of polarisation optics.



Schematic layout of **SFG Classic** spectrometer

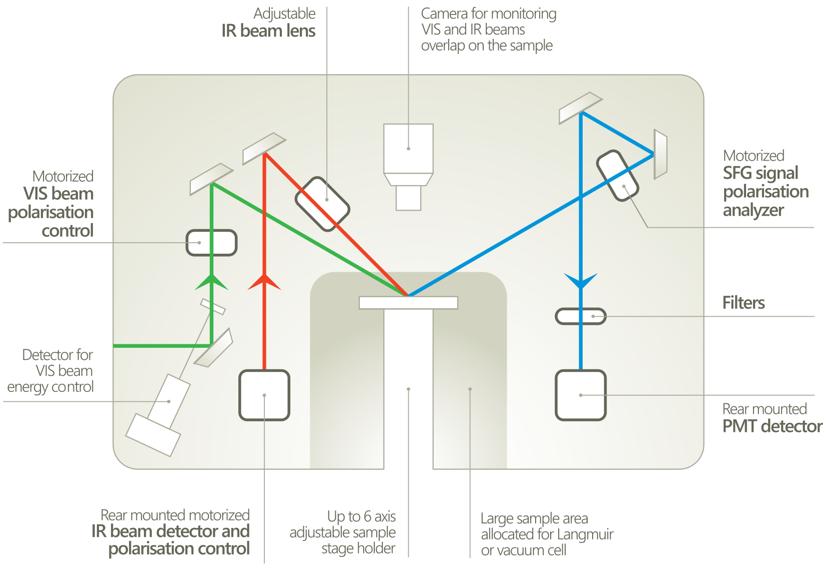
The new SFG classic spectrometer consist of two units: laser light source PT501 and spectroscopy module.

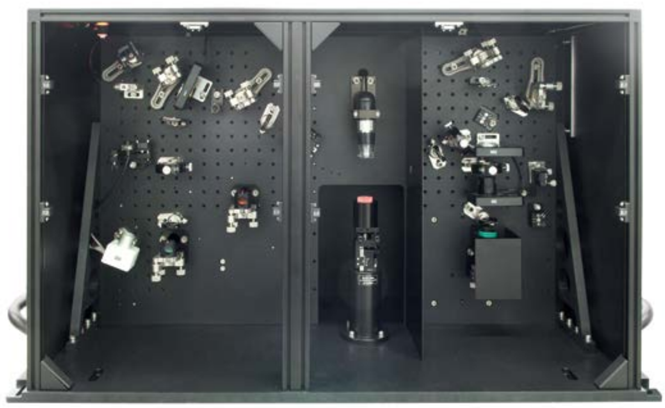
The Ekspla SFG system is based on a mode-locked Nd:YAG laser with a 29 ps pulse duration, 100 Hz repetition rate. The VIS channel of the SFG spectrometer consists of part of a laser output beam, usually with doubled frequency (532 nm) up to 0.3 mJ. The main part of the laser radiation goes to an optical parametric generator (OPG) with a difference frequency generation (DFG) extension. The IR channel of the spectrometer is pumped by the DFG output beam with energy in the range of ~40 – 200 µJ. Infrared light can be tuned in a very broad spectral range from 2.3 up to 16 µm. The bandwidth is 3 cm^{-1} and it is one of the main factors of SFG spectrometer spectral resolution. The second beam (VIS) is also narrowband at <2 cm^{-1}. The spectrometer signal detection system has a temporal gate. It significantly reduces accumulative noise and ambient light influence, which allows to use spectrometer even in a brightly illuminated room. The spectrometer does not have any acoustic noise because the laser is pumped by light emiting laser diodes. The spot size of the IR beam is adjustable. In this way, the appropriate energy density is achieved in order to avoid damaging or modifying the sample. Spectrum scanning, polarisation control and VIS beam attenuation are controlled from a computer. The spectrometer has a motorized polarisation switch for the IR, optionaly for the VIS, and optionaly the generated SFG light beams. Energy detectors continuously monitor the energy of the VIS and mid-IR laser pulses, so IR energy is recorded at each measurement point. This makes it possible to normalise the resulting SFG vibrational spectrum.

Fast wavelength scan (sweep) allows fast access to a wide spectral range. Using time-synchronised motor positions enables fast and smooth wavelength tuning which allows users to scan the full range in just a few seconds or access specific wavelengths within 0.3 seconds.

SPECTROSCOPY MODULE, SAMPLE COMPARTMENT

A large sample compartment can be customised and enables the use of various extensions and additional instruments for simultaneous control of the sample conditions, including a Langmuir-Blodgett trough for air/water and lipid/air interface studies, temperature and humidity-controlled cells, and other instruments.



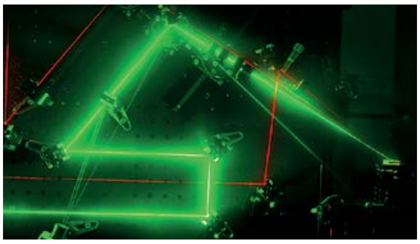


Standard layout of the vertically-arranged sample compartment of the SFG spectrometer

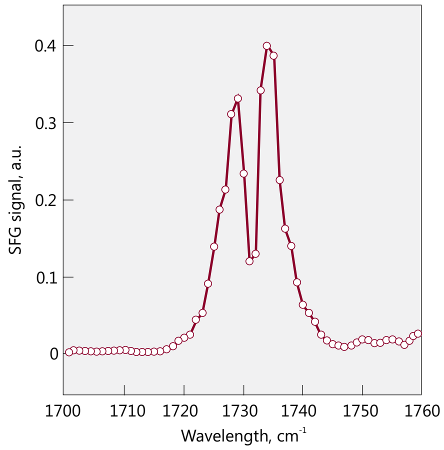
SAFETY OF THE SFG SPECTROMETER

The spectrometer is safe to use: all high energy pulsed beams are enclosed. In addition, the sample area also has a special cover. During the measurements, it is possible to close the sample compartment so that radiation cannot penetrate outside.

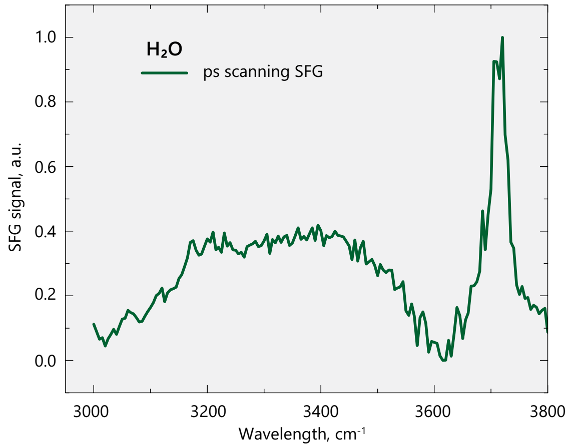
The automatic change of polarisation and energy attenuation makes it possible to perform measurements without opening the spectrometer. Laser safety precautions are required only for the alignment of the laser beams on the studied surface.



SPECTRA EXAMPLES



SFG spectra of monoolein surface, 1 cm^{-1} scan step, 200 acquisitions per step



Water-air interface spectra, 200 acquisitions per step

Picosecond scanning SFG spectrometer Modifications and Options

DOUBLE RESONANCE MODEL

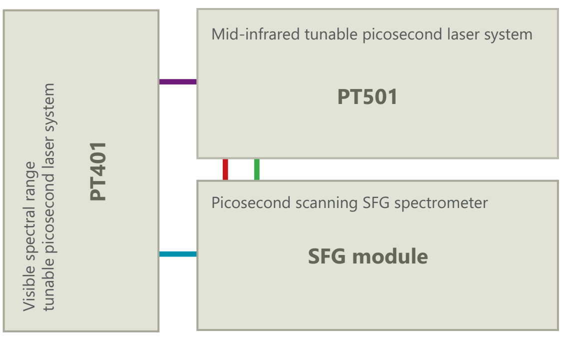
Both IR and VIS wavelengths are tunable in Double resonance SFG spectrometer model.

This two-dimensional spectroscopy is more selective than single resonant SFG. Double resonant SFG allows investigation of vibrational mode coupling to electron states at a surface.

Double resonance enables the use of another wavelength for VIS beam if the sample has strong absorption at 532 nm and 1064 nm. A range 420 – 680 nm is typically used for VIS beam.

The second tunable laser system is used for the double-resonance SFG. Two laser systems PT501 and PT401 are opticaly synchronised.

* Laser is located in the PT501 system. System PT401 can not operate separately from PT501.



Schematic layout of SFG double resonsnce spectrometer

MODIFICATIONS

- *Double resonance SFG spectrometer – allows investigation of vibrational mode coupling to electron states at a surface*
- *Phase sensitive SFG spectrometer – allows measurement of the complex spectra of surface nonlinear response coefficients*

OPTIONS

- *Single or double wavelength VIS beam: 532 nm and/or 1064 nm*
- *One or two detection channels: main signal and reference*
- *Second harmonic generation surface spectroscopy option*
- *Motorized polarisation control for VIS and SFG beams*
- *Larger sample compartment to accomodate Langmuir through*
- *Simultaneous measurement of s and p polarisation of SFG signal*

PHASE-SENSITIVE SFG SPECTROMETER

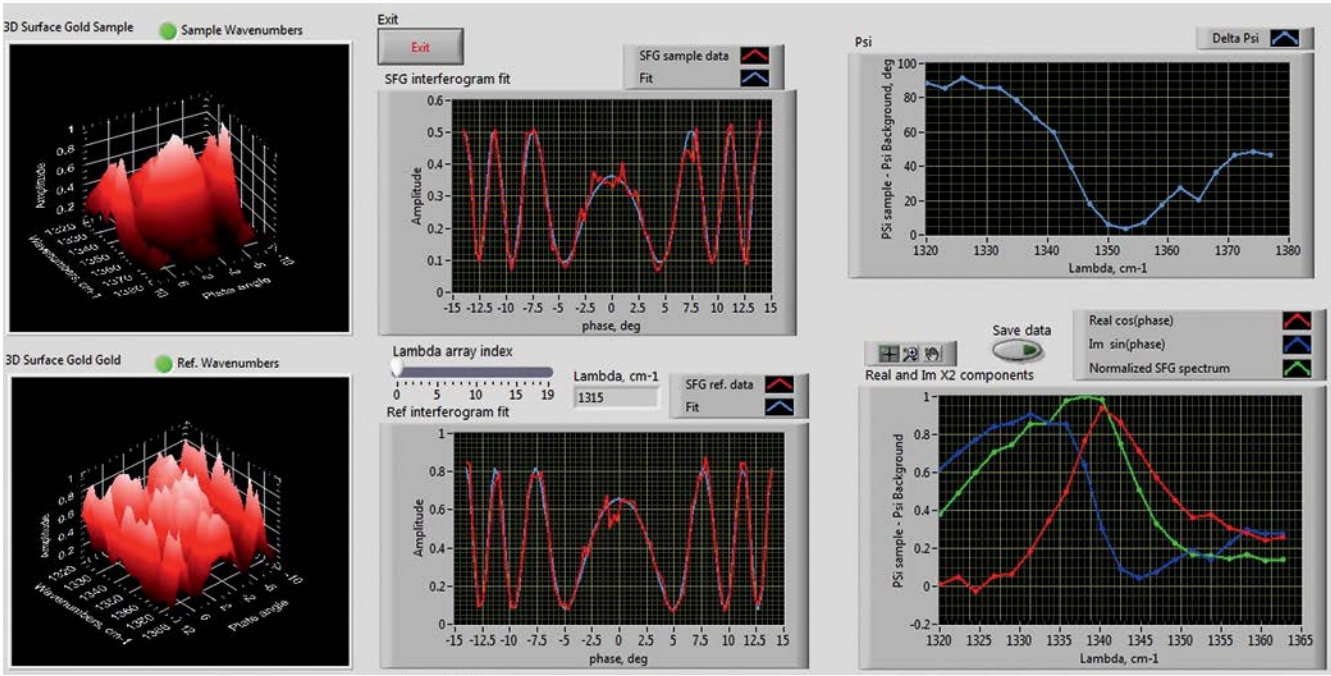
Phase sensitive measurements

A phase sensitive spectrometer allows the measurement the phase of nonlinear susceptibility $\chi^{(2)}$. Reference and test samples are used and the SFG phase difference between them is scanned. The real and imaginary parts of second order susceptibility are calculated from the experimental results. Such an approach enables the unambiguous determination of the orientation of molecular groups at the interface.

In conventional SFG-VS intensity of SF signal is measured. It is proportional to the square of second order nonlinear susceptibility $I_{SF} \sim |\chi^{(2)}|^2$. However, $\chi^{(2)}$ is complex, and for complete information, we need to know both the amplitude and the phase. This will allow us to determine the absolute direction in which the bonds are pointing and characterize their tilt angle with respect to the surface.

Measurement of the phase of an optical wave requires an interference scheme. Mixing the wave of interest with a reference wave of known phase generates an interference pattern, from which the phase of the wave can be deduced.

In practice Phase-sensitive SFG experimental setup includes two samples generating SF signal simultaneously. One sample (usually called local oscillator) has well known and flat spectral response. Second one is investigated sample. The excitation beams are directed to first sample, where SFG beam is generated. Later all three beams are retranslated to the second sample, where another SFG beam is generated. Due to electromagnetic waves coherence both SFG beam are interfering. Setup contains the phase modular located on the SFG beam path between samples. We are able to change the phase of SFG beam by rotating it. This way we are recording two-dimensional interfererogram with wavelength and phase shift on x and y axis. Using fitting algorithms we are able to calculate the amplitude and phase of SF signal.



Phase-sensitive SFG spectrometer software window showing interferograms of AZO (azophenylcarbazole) dyes on the Au surface and fitted SF spectra with amplitude and phase distinguished

PHASE SENSITIVE SFG + CLASSIC SFG SPECTROMETER IN ONE UNIT

Interference measurements of SFG signals from reference sample and the investigated sample for Phase-sensitive configuration.

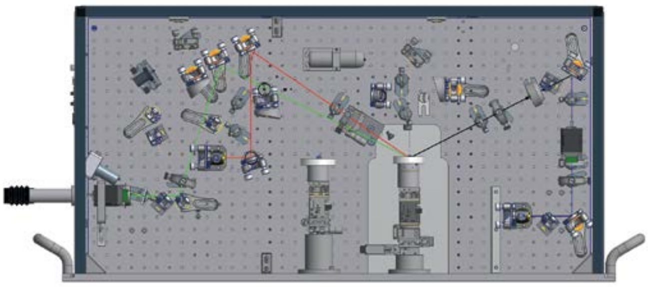
Switchable setup. Phase Sensitive / "Classic" Top configuration.
Switch: VIS beam manual. IR mirror mount is motorised, lens positioning stage is manual.
Path length to the sample is same in all configuration
Motorised polarisation control.
VIS beam 532 nm. IR 2.3 – up to 16 µm.

OPTIONS

Spectrometer has "Classic" and "Phase-sensitive" properties:

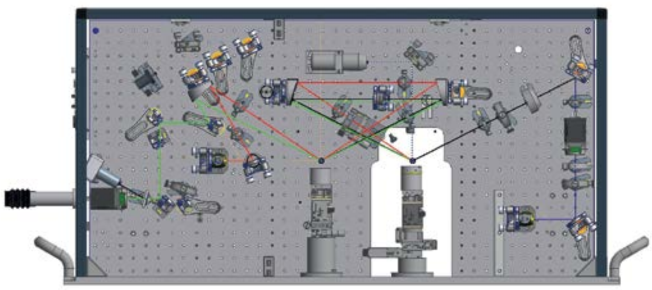
- *Easy switching between setups*
- *Adjustable spot size for classic configuration*

"Classic" configuration



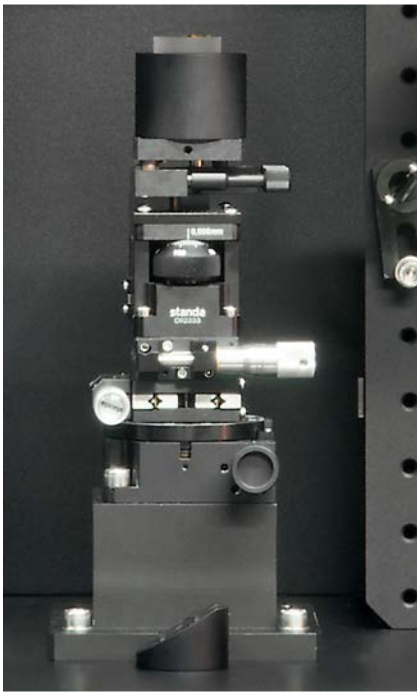
Tunable beam size for IR beam.
Beams are focused with lens. (BaF_2 lens for IR beam).
"Classic" configuration. IR 2.3 – 16 µm.

Phase sensitive, Top (Reflection- Reflection) configuration

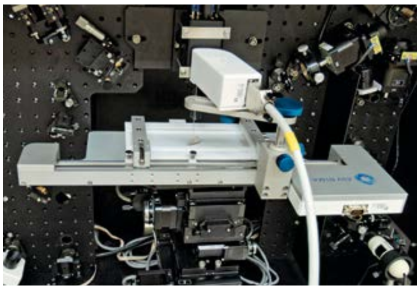


Fixed beams sizes on the sample. VIS and IR beams.
Beams are focused with parabolic mirrors.
Interference configuration for phase measurement.
IR 2.3 – 10 µm.

SFG Spectrometer Accessories



Compact and stable six axis manipulator for precise sample positioning.
Motorised version available as an option



SFG spectrometer with Langmuir trough used for studies of the unique properties of molecules in monolayers

Hermetically sealed sample cell with heater (temperature range 20 – 70 °C), specially designed for SFG spectrometer, allows experiments under controlled environmental conditions

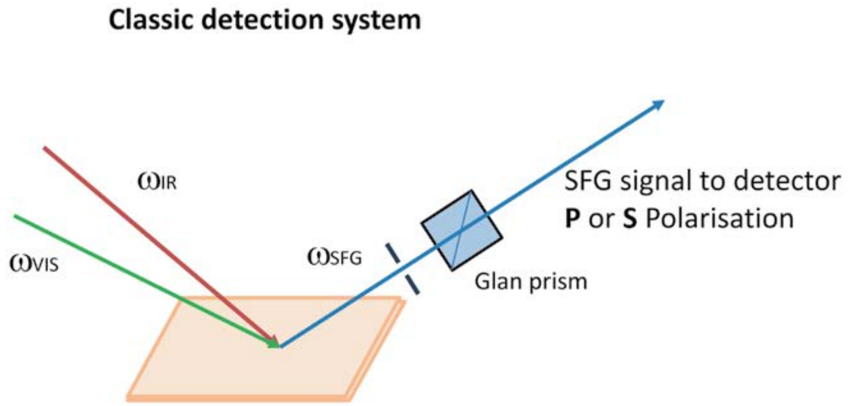
OPTIONAL ACCESSORIES

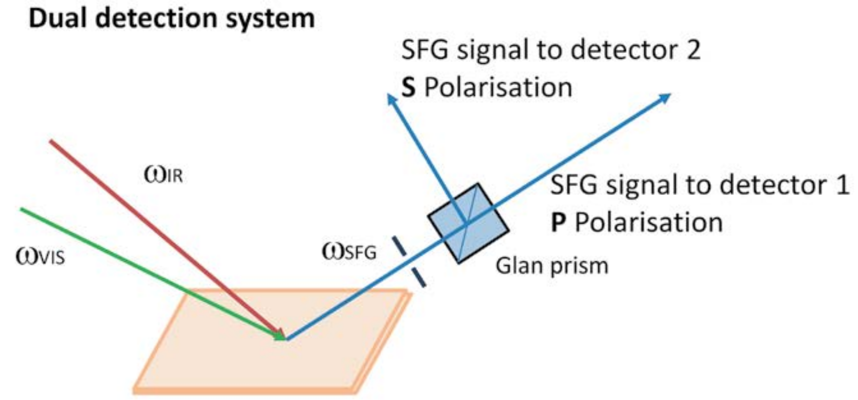
- *Six axis sample holder*
- *Sealed temperature controlled sample chamber*
- *Larger sample area – space for Langmuir trough*
- *Motorisation of polarisation control of VIS and IR beams, polarisation analyser for SFG signal*

SFG Spectrometer polarisation control options

SIMULTANEOUS MEASUREMENT OF S AND P POLARISATION

S and P polarisation of the SFG signal are detected during the same measurement in the dual polarisation detection system.

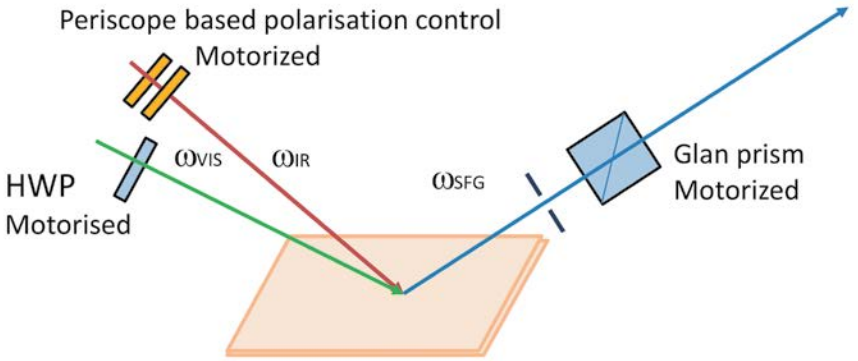




MOTORIZED POLARISATION CONTROL OF SFG, VIS, IR

The SFG spectrometer has a motorized polarisation switch for the IR, VIS, and the generated SFG light beams. The automatic change of polarisation and energy attenuation makes it possible to perform measurements without opening the spectrometer.

- Motorized switching of IR – standard
- Motorized control in small steps of SFG, VIS – optionally



Technical specifications [1)] of picosecond scanning SFG spectrometer

Version	SFG Classic	SFG Double Resonance	SFG Phase Sensitive
SYSTEM (GENERAL)			
Spectral range	625 – 4300 cm^{-1}	625 – 4300 cm^{-1} (VIS 532 nm) 1000 – 4300 cm^{-1} (VIS 420 – 680 nm)	1000 – 4300 cm^{-1}
Spectral resolution	<3 cm^{-1}		
Spectra acquisition method	Scanning and fast wavelength sweep		
Sample illumination geometry	Top side, reflection		
Incidence beams geometry	Co-propagating, non-colinear		
Incidence angles	Fixed, VIS ~60°, IR ~55° (optional: tunable)		Fixed, VIS ~60°, IR ~55°
VIS beam wavelength	532 nm	532 nm and tunable 420 – 680 nm	532 nm
Polarization (VIS, IR, SFG)	Linear, selectable "s" or "p", purity > 1:100		
IR Beam spot on the sample	Adjustable, ~200 – 600 µm		Fixed
Sensitivity	Air-water interface spectra		Solid sample spectra
LASER LIGHT SOURCE [2)]			
Model	PT501-SH		
Pulse duration (pump laser)	29 ± 5 ps		
Pulse repetition rate	100 Hz		
VIS source for Double resonance SFG	–	PT401	–

For standard specifications please check the brochure of particular model.

PHYSICAL DIMENSIONS (FOOTPRINT)			
Standard	1300 × 1200 mm	1800 × 1200 mm	1400 × 1200 mm

1) Due to continuous improvement, all specifications are subject to change without advance notice.
2) Laser is optimised for pumping parametrical generator, maximum output energy may be different than specified for stand alone application.

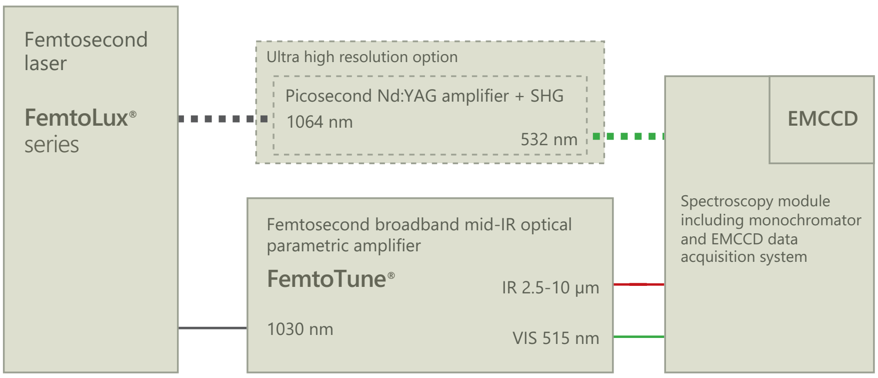
Features and design of the broadband femtosecond SFG spectrometer

Femtosecond broadband SFG (BB SFG) spectrometer allows fast SFG spectra acquisition since most vibrational modes can be resolved without scanning. The advantage of the broadband SFG system is that intense femtosecond pulses allow efficient sum frequency generation at low pulse energies thus reducing the possibility of sample modification. It is especially important for aqueous and biological samples.

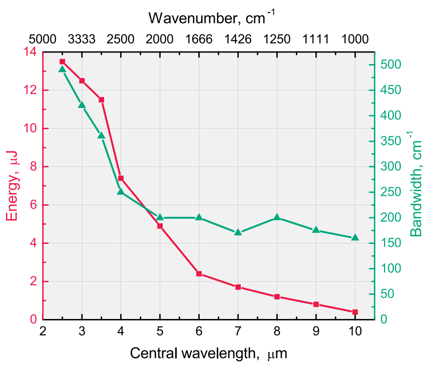
The system is based on a femtosecond industrial grade FemtoLux® series laser with 500 fs pulse duration, more than 1 mJ pulse energy at 1030 nm and a 1 kHz repetition rate. The main part of the laser radiation is directed to a broadband mid-IR OPA module. Broad bandwidth (150 – 450 cm^{-1}) mid-IR radiation can be continuously tuned in a spectral range from 2.5 up to 10 µm, providing from 0.5 to 12 µJ close to energy transform-limited pulses for the IR channel. The VIS channel implementation depends on the system configuration. In a standard setup, a part of laser output radiation is frequency doubled (515 nm) ~20 µJ and then spectrally filtered to produce <8 cm^{-1} bandwidth pulses. High resolution version consists of optically synchronised femtosecond and picosecond lasers. The combination of broadband mid-IR and narrowband VIS radiation allows to get the broadband sum frequency signal with exceptionally high spectral resolution below <3 cm^{-1}.

Fast wavelength scan (sweep) allows fast access to wide spectral range. Using time-synchronised motor positions enables fast and smooth wavelength tuning which allows users to scan the full range in just a few seconds or access specific wavelengths within 0.3 seconds

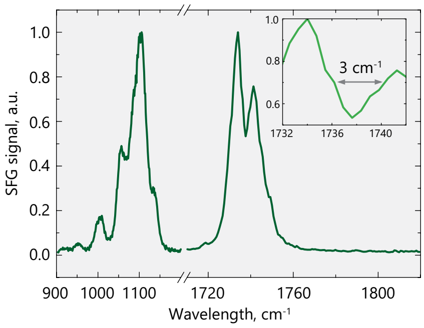
This allows shifting the central wavelength countinuously during accumulative SFG measurements, effectively broadening the mid-IR bandwidth of a single acquisition and smoothing the mid-IR spectrum for better normalisation. Continuous, gapless tuning from 2.5 to 10 µm with a single polarisation ensures stable beam pointing, enabling seamless spectral measurements across the entire mid-IR range.



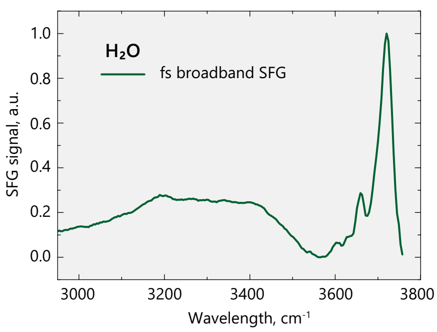
Schematic layout of BB SFG spectrometer



Mid-IR parametrical amplifier characteristics. Energy and spectral bandwidth versus central wavelength



Spectral resolution of 3 cm^{-1} demonstrated by measuring monoolein SFG spectrum. Dip in the spectrum caused by narrowband water absorption, thus used to estimate resolution



Pure water spectrum. Spectrum acquisition time 10 min

Technical specifications [1) of broadband femtosecond SFG spectrometer

Version	SFG fs	SFG fs High Resolution
SYSTEM (general)		
Spectral range	1000 – 4300 cm^{-1}	1000 – 4300 cm^{-1}
Spectral resolution	< 9 cm^{-1}	< 3 cm^{-1}
Spectral bandwidth [2)	150 – 450 cm^{-1}	
Spectra acquisition method	Broadband accumulative	
Sample illumination geometry	Top side, reflection	
Incidence beams geometry	Co-propagating, non-colinear	
Incidence angles	Fixed, VIS ~60°, IR ~55° (optional: tunable)	
VIS beam wavelength	515 nm	532 nm
Polarization (VIS, IR, SFG)	Linear, selectable “s” or “p”, purity > 1:100	
Beam spot on the sample	Adjustable, ~200 – 600 μm	
Sensitivity	Air-water spectra	
PHYSICAL DIMENSIONS (footprint)		
Standard	2000 × 1500 mm	2200 × 1500 mm

1) Due to continuous improvement, all specifications are subject to change without advance notice.
2) Measured at 30% level.

Title / subject	Date
Notes	Signatures

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