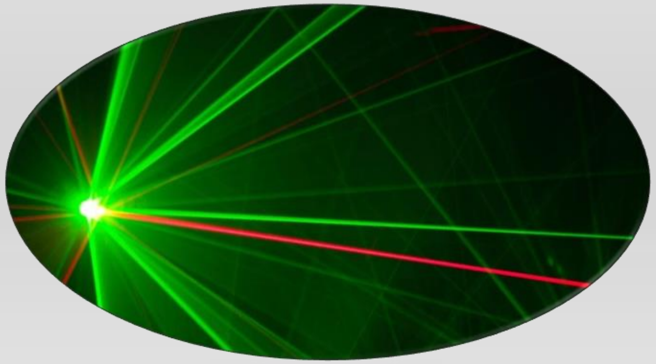


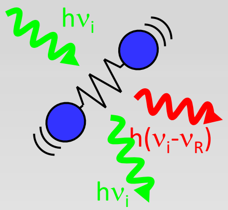
Stimulated Raman Scattering Spectroscopy Tutorial

Raman spectroscopy background

- Today 90% of the industrial spectroscopy instruments based on IR absorption (Near-IR, Mid-IR , FT-IR or other techniques)
- Raman spectroscopy based on Raman phenomena (1928)
  - Sir Chandrasekhara Raman, (1930 physics Nobel Prize)
- Every compound possesses a unique “Raman-fingerprint” – a molecule can be recognized by its Raman spectrum.
- Lab analyzers based on Raman spectroscopy are successfully operated in the chemicals, material and Pharma industries for more than 15 years but only for solid and liquids (not for gases)

Prior Art

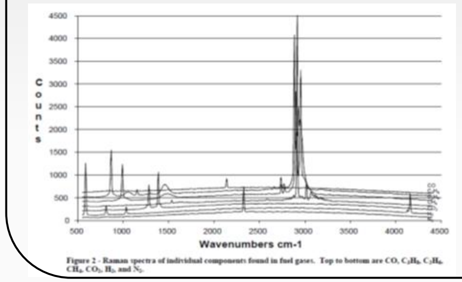
Illumination laser: “pump”



Raman shifted Photons (0.00001%) – longer wavelengths are called “Stokes”

elastically scattered Photons (99.99999..%)

Raman fingerprint of Natural Gas



Professor Sir C.V. Raman 1888-1970

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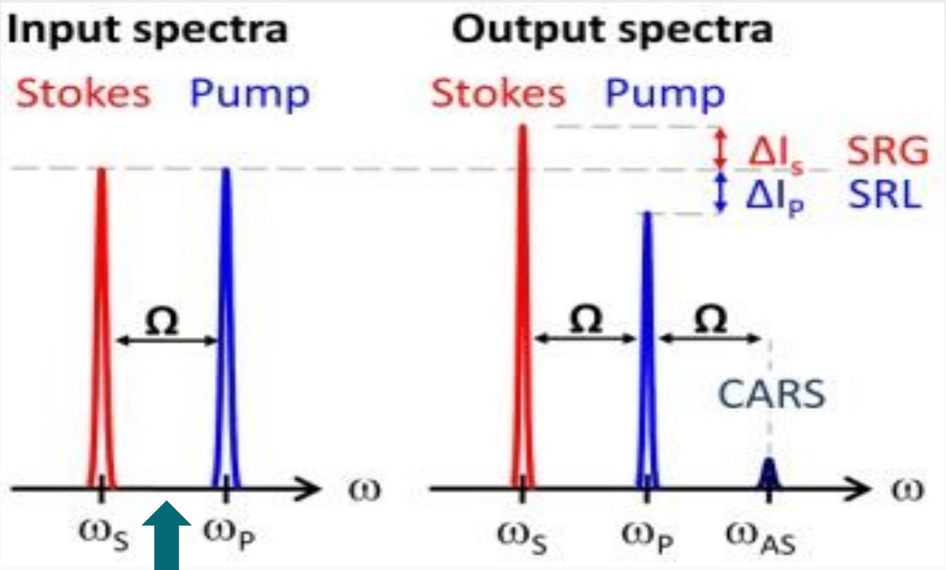
Quantum Optics Analysis

SRS (Stimulated Raman Scattering) Spectroscopy

Prior Art

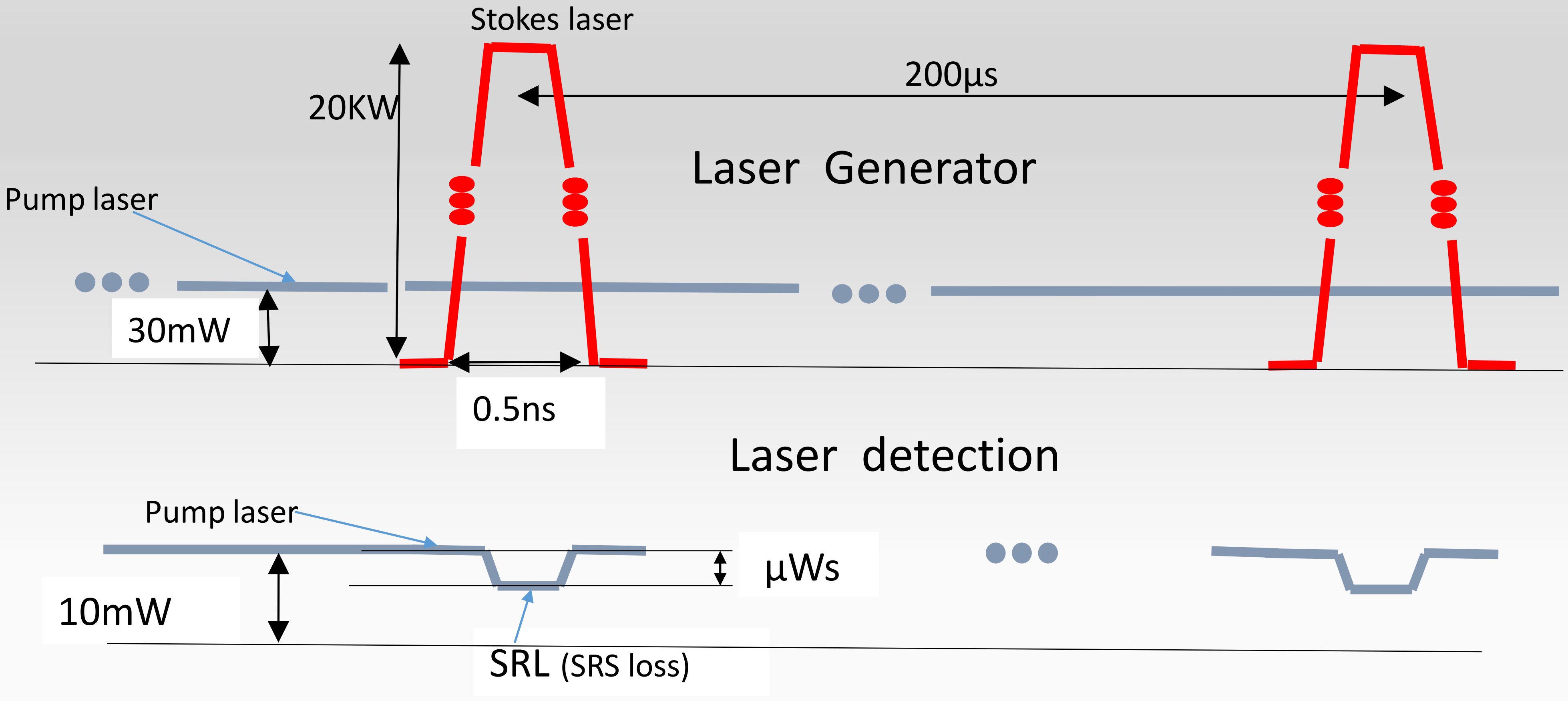
- SRS is advanced technique to generate Raman spectrum, as of today it is being used by research lab in the academia only
- In SRS, two high intensity lasers illuminate a sample in predefine spectral distance, in accordance to the known Raman spectrum of the molecule. these are called "Pump" and "Stokes".
- In SRS the Raman phenomena is magnified (> X 100,000) enables high resolution and fast response time spectroscopy
- Spectrometers based on SRS capable to measure very low concentrations even in the gas phase



- Energy is transferred from one beam to the other
- The amount of energy transferred is proportional to the molecule concentration

The spectral distance is unique to the target molecule (Equal to the molecule's Raman shift)

SRS implementation



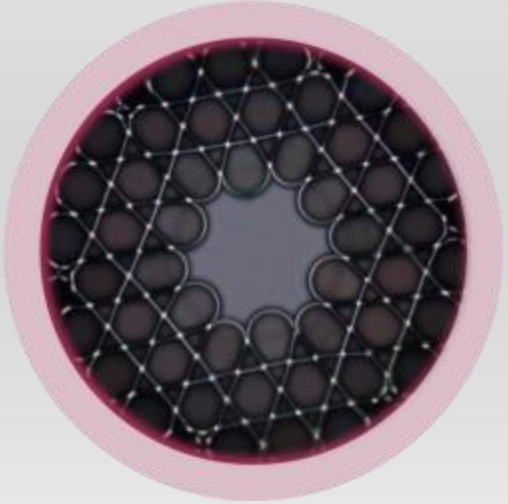
SRL $\propto$ C × σRaman × Ip × Is (Linear approximation)

- C: Ttarget molecule concentration
- σRaman: Raman cross section of the target molecule
- Ip: Pump intensity
- Is: Stokes intensity

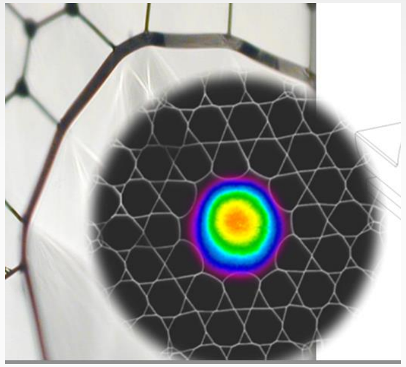
SRS spectroscopy challenges

- Illumination of two lasers on the target sample
  - Each target molecule enforces different spectral distance between the lasers
  - Implemented with high power pulse laser (Stokes) at 1064nm and CW tunable laser as Pump
    - Example: to measure 10 gases requires illumination of 10 different pump wavelengths
  - For some of gases the corresponded wavelength is out of the range of the tunable laser (920-980 nm) and additional fixed lasers are required
  - The intensity of the two lasers must be very high- $I_p \times I_s > 10 GW/cm^2$
    - Can be achieved with high power lasers and very small fucus
  - The spatial alignment and the spectral alignment of the two lasers must be very accurate
    - Special mechanism implemented to achieve it.
- Acquire the SRS signal
  - In low concentration gas the SRS signal (SRG/SRL) are very low (below the naturel noise of the system) requires ~ 60-80 dB SNR improvement
  - Very low signal duty cycle – make the acquisition very challenges
    - The SRS signals are very short (< 1ns) in relatively low repletion rate (~5KHz)
  - Wide range of concentrations (99% to 10 PPM) require receiving wide range of SRS signal amplitudes

Hollow Core Photonic Crystal fibers



- A hollow-core fiber is an optical fiber which guides light essentially within a hollow region, so that only a minor portion of the optical power propagates in the solid fiber material (typically a glass). A particular architecture is a a **photonic crystal fiber** containing a pattern of silica rings (with circular or elliptical cross-section) around the hollow core.



- The hollow cores subsystem is being codeveloped with with GLOphotonics SAS (France) a world leader in HCPCF* development.

GLOphotonics

https://www.glophotonics.fr/

* HCPCF – Hollow Core Photonic Crystal Fiber.

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Implementation of SRS in hollow core fibers

- The hollow region of the fiber is relatively small (~50µm ϕ) The gas is located (stationary or flow through) in that region. This confined environment is optimal for the quantum-optics interaction (SRS in our case) between the gas and the laser, as the laser intensity is very high across the full length of the fiber. SRS amplification is exponential with the interaction length and permitted only above high level of light intensity
- This unique SRS Implementation enables:
  - implementation of SRS with Single laser
  - Configurable system One system fits all gases
  - Wide dynamic range – sub PPM to 100%
  - Microfluidic gas supply