502 35100

量測原理與機工實驗

IV. Laser Diagnostics for Thermofluid Measurements

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  - Background and principle
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- A study of measuring flow velocity and species
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  - Mie scattering
  - Rayleigh scattering
  - Raman scattering
  - CARS
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References :

R. J. Goldstein, *Fluid Mechanics Measurements*, Hemisphere, 1983
S. Tavoularis, *Measurement in Fluid Mechanics*, Cambridge Univ., 2005
A. C. Eckbreth, *Laser Diagnostics for Combustion Temperature and Species*, Abacus Press, 1988

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Introduction to Laser

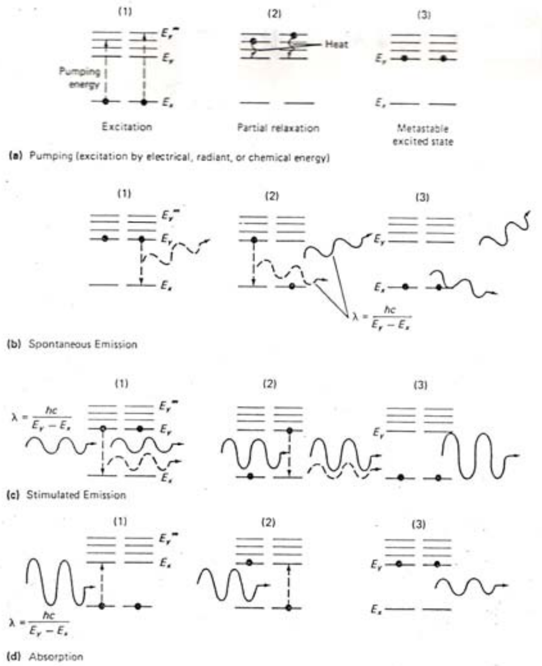
- Acronym: light amplification by stimulated emission of radiation
- Advantages as compared with thermal light sources
  - Coherent (with all light fronts in phase)
  - Collimated and concentrated (essentially parallel, with a small cross-sectional area)
  - Monochromatic (with spectral energy concentrated in one or more extremely narrow band)
- Disadvantages
  - Diffraction due to dust particles → *speckles*: distortion by fringes and patterns; partly removed by a pinhole (spatial filter)

- Principle
  - Active medium: gas, crystal, semiconductor, liquid solution …
  - Medium composed of particles (atoms, ions, or molecules), with electrons existing only at specific quantized energy levels

  – *absorption* and *spontaneous emission*: random direction

  – *stimulated emission*: coherent emission of an incident photon, with identical frequency (energy), phase, and direction

  – *population inversion*: for effective stimulated emission, larger population of atoms at a high energy state than at a lower state
- Use (nonintrusive): flow visualization, measurements for velocity, pressure, temperature, and composition, both in liquids and gases



- Components
  - Energy pump source: in the form of electromagnetic or chemical energy provided by an electric discharge, a flash lamp, or another laser

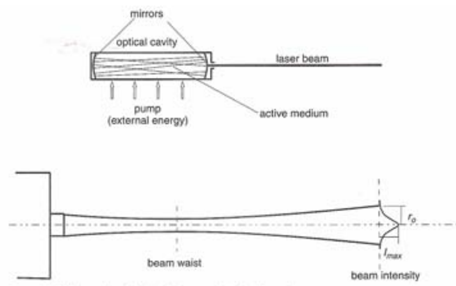


Figure 5.7. Schematics of a basic laser and a typical laser beam.

Photocopied from Tavoularis (2005)

  - Optical cavity: a tube with two plane or concave mirrors at the ends

– Standing waves: distance between two mirrors being adjusted to an integral multiple of light wavelength $\lambda/2$

– One of the mirrors being slightly transparent

- Quality factor (*Q*) and Q-switching
  - *Q*: energy decay, high better
  - Produce large laser pulses
- Modes of standing waves
  - Longitudinal mode

– Multiples of $\lambda/2$

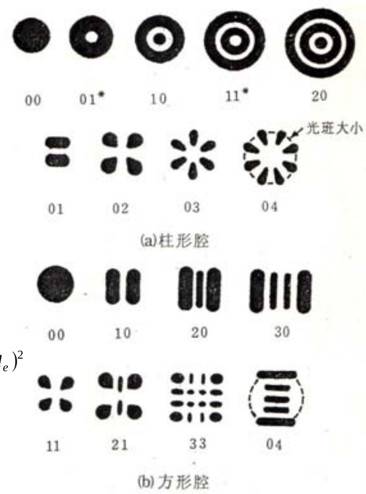
– Adjust distance between mirrors

  - Transverse mode $I_a(r) = I_{a\max} e^{-2(2r/d_e)^2}$

– Fundamental mode ~ Gaussian

– d_e ~ circle with $e^{-2} I_{a,\,max} \approx 13.5\%$

  - Preferred due to smallest beam divergence, diameter, and spatial coherency though with lower power



- Laser types: continuous wave (CW) type, single pulse, repetitive pulses
  - *Solid-state* lasers:

– broad and effective absorption band, high fluorescence efficiency, long life, narrow fluorescence band of wavelength

– population inversion, stimulated emission

– Ex. Ruby laser: Al_2O_3:Cr^{3+}, Nd:YAG laser: $Y_3Al_5O_{12}$:Nd^{3+} (Neodymium doped Yttrium Garnet Laser釹玻璃雷射, 釹玻璃+釔鋁石榴石晶體)

  - *Gas* lasers:

– atomic: He, Ne, Ar, Kr, Xe

– molecular: CO_2, CO, N_2, H_2, HF

– ionic: Ar^+, Kr^+, Cd metallic ion

  - *Semiconductor* lasers: GaAs
  - *Liquid* lasers:

– organic dye solution: broad spectrum, tunable

– inorganic liquid: $SeOCl_2$:Nd^{3+}, $POCl_3$:Nd^{3+}

▪ Laser types (Cont'd)

• *Helium-neon* (He-Ne) lasers: CW type, power 0.3 – 15 mW, at λ = 633 nm (red)

– easy operation and low cost, flow visualization

– active medium composed of helium and neon atoms

– energy pump source of high-voltage (~ 2000 V) electric field

• *Argon-ion* (Ar) lasers: CW type, power 100 mW – 10 W, at 7 wavelengths particularly λ = 488 (blue) and 514.5 nm (green)

– low power efficiency, water/air cooling

– for flow visualization, LDV, PDPA, PIV …

– active medium of argon atoms, at ion state with collision by electrons accelerated via *E* field, in a plasma tube

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• *Nd:YAG* lasers 釹釔鋁石榴石雷射: solid-state pulsed lasers

– active medium of neodymium (Nd^{+3}) as an impurity into a crystal of yttrium aluminum garnet (YAG) serving as a host

– energy pump source of a flash lamp

– in a single pulse mode: pulses with energy 100 – 400 mJ and 100 ps – 10 ns, with *Q*-switch

– main emission at λ = 1064 nm (infrared) but 532 nm available via frequency doubling or tripled in ultraviolet range with special crystal

– give a train of pulses at repetition rates exceeding 1 kHz, with pumping provided by a CW diode laser

• *Copper-vapor* (Cu) lasers: repetitive pulses 15 – 60 ns, 10 mJ per pulse, 5 – 15 kHz, mainly at λ = 510.6 (green) and 578.2 nm (yellow)

– unlike others with cooling, insulated to achieve high operating *T*

– suitable for particle tracking, flow visualization, PIV …

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• *Dye* lasers: substance used for dying fabrics

– active medium of complex, multi-atomic, organic molecules

– continuous emission spectra over wide λ bands of 200 – 1500 nm

– energy pump source of a flash lamp or other lasers

– when pumped by a Nd:YAG laser, in combination with frequency filters contained in the optical cavity, tuned to emit radiation at narrow bands matching resonant frequencies of various molecules

– for measurement of species concentration (gas mixtures, combustion…)

• *Excimer* lasers: e.g. KrF and XeCl, used specifically in combustion

– active medium of diatomic molecules, whose atoms are bound attractively only if one of them is at an excited electronic state (exciplexes) but dissociate at the ground state

– emit ultraviolet and high-energy pulses at high repetition rate

• *CO_2* lasers:

– active medium of CO_2 molecules at ground state

– oscillate at $\lambda = 10.4$ μm (infrared), either in continuous or pulsed mode

– population inversion to higher vibrational energy states caused by collisions with nitrogen molecules at a metastable, excited vibrational mode; pumped thermally

• *Laser diodes*:

– semiconductor devices that emit coherent radiation in visible or infrared ranges when current passes through

– used extensively in optical-fiber communication systems, compact disc players, laser printers, remote controls, and intrusion detection systems

– much smaller than conventional lasers and lower power requirement

– high-power laser diodes used for flow visualization, LDV, PIV …

- Illumination techniques

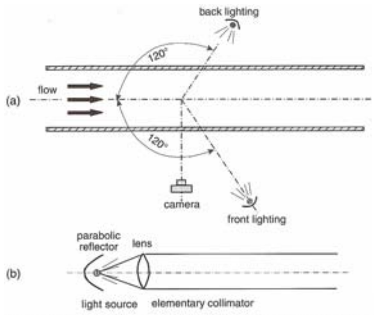

Figure 5.9. Sketches showing (a) optimal illumination arrangements and (b) an elementary light collimator.

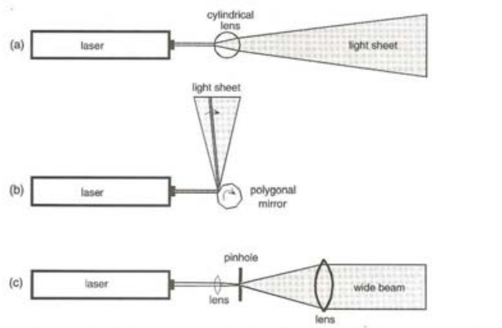

Figure 5.10. Conversion of a laser beam into (a) a light sheet with the use of a lens, (b) a light sheet with the use of a polygonal mirror, and (c) a wide beam.

Photocopied from Tavoularis (2005)

LDV for Velocity Measurement

- Acronym: laser Doppler velocimetry (LDV) or anemometry (LDA)
- Advantages as compared with conventional techniques
  - Non-intrusive, linear relation between flow velocity and Doppler frequency (no calibration and errors reduced), rapid response and high temporal resolution, high spatial resolution (1 mm^3), large speed range, reversed flow, temperature insensitive
- Disadvantages
  - Transparent windows, seeding particles that follow flows (rate), complex alignment, not-so-easy signal processing with weak scattering light and interruption from different particles (low SNR)

- Basic principle
  - Doppler shift of light frequency: *Doppler (-Fizeau) phenomenon*

– Doppler frequency: for a monochromatic, coherent, linearly polarized, and collimated laser beam

$$\nu_D = \frac{\vec{V}\cdot(\vec{e}_s - \vec{e}_i)}{\lambda} = \frac{2\sin(\phi/2)}{\lambda}V_\phi$$

– generally not possible to measure $\nu_D << \nu$ unless for large V_ϕ

$\nu \approx 10^{14}$ Hz

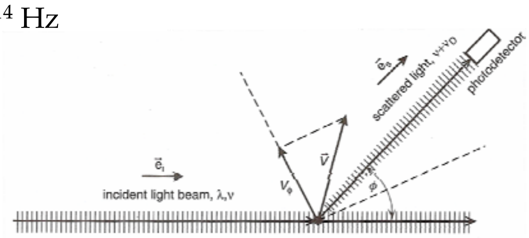

Figure 11.9. Sketch of a laser beam light scattered by a moving particle.

Photocopied from Tavoularis (2005)

- Dual-beam LDV: single component, forward scatter

– beam splitter: monochromatic, coherent, linearly polarized beam

– output voltage via a photodetector $E \sim A^2$

$$E \sim \{A_1 \sin 2\pi[(\nu+\nu_{D1})t] + A_2 \sin 2\pi[(\nu+\nu_{D2})t]\}^2$$
$$= A_1^2 \sin^2 2\pi[(\nu+\nu_{D1})t] + A_2^2 \sin^2 2\pi[(\nu+\nu_{D2})t]$$
$$+ A_1 A_2 \{\cos 2\pi[(\nu_{D1}-\nu_{D2})t] - \cos 2\pi[(2\nu+\nu_{D1}+\nu_{D2})t]\}$$

– *Doppler frequency difference* and signal

$$\nu_D' = \nu_{D1} - \nu_{D2}$$
$$E \sim a + b\cos 2\pi\nu_D'$$

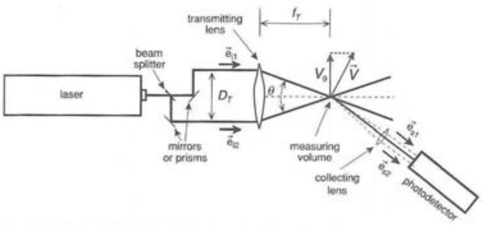

Figure 11.10. Sketch of the dual-beam laser Doppler configuration.

Photocopied from Tavoularis (2005)

– *Doppler frequency difference*

$$\nu'_D = \frac{\vec{V}\cdot(\vec{e}_{s1}-\vec{e}_{i1})}{\lambda} - \frac{\vec{V}\cdot(\vec{e}_{s2}-\vec{e}_{i2})}{\lambda}$$

$$= \frac{\vec{V}\cdot(\vec{e}_{i2}-\vec{e}_{i1})}{\lambda} = \frac{2\sin(\theta/2)}{\lambda}V_\theta \qquad V_\theta = \frac{\lambda}{2\sin(\theta/2)}\nu'_D$$

– *Measuring volume and fringe model*

Focused beam diameter $d_{fe} \cong \dfrac{4 f_T \lambda}{\pi d_e}$

$$h = \frac{d_{fe}}{\cos(\theta/2)} \qquad l = \frac{d_{fe}}{\sin(\theta/2)}$$

$$\xrightarrow{\text{measuring volume}} \frac{\pi d_{fe}^3}{6\cos(\theta/2)\sin(\theta/2)}$$

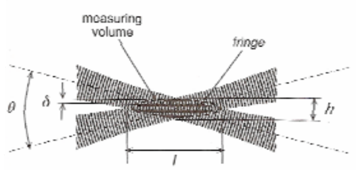

Figure 11.11. Measuring volume and fringe pattern in the dual-beam configuration.

– *Fringe spacing* $\delta = \dfrac{\lambda}{2\sin(\theta/2)}$

and crossing frequency V_θ/δ

Photocopied from Tavoularis (2005)

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- More on LDV working principles
  - Doppler shift of light frequency

– Frequency observed by a particle

$$f_p = \frac{c-\mathbf{u}\cdot\mathbf{l}}{\lambda} = f\left(1-\frac{\mathbf{u}\cdot\mathbf{l}}{c}\right) \qquad \mathbf{l} = -\boldsymbol{\ell}$$

– Frequency observed by detector

$$\lambda_A = \frac{c-\mathbf{u}\cdot\mathbf{k}}{f_p} \rightarrow f_A = \frac{c}{\lambda_A} = \frac{f\left(1-\frac{\mathbf{u}\cdot\mathbf{l}}{c}\right)}{1-\frac{\mathbf{u}\cdot\mathbf{k}}{c}}$$

$$\Delta f = f_A - f = \frac{\mathbf{u}\cdot(\mathbf{k}-\mathbf{l})}{\lambda\left(1-\frac{\mathbf{u}\cdot\mathbf{k}}{c}\right)}$$

$$\Delta f \sim \frac{1}{\lambda}\mathbf{u}\cdot(\mathbf{k}-\mathbf{l}) \qquad c \gg u$$

Photocopied from 黃清白，楊鏡堂，科儀新知，第十一卷，第六期 79.5

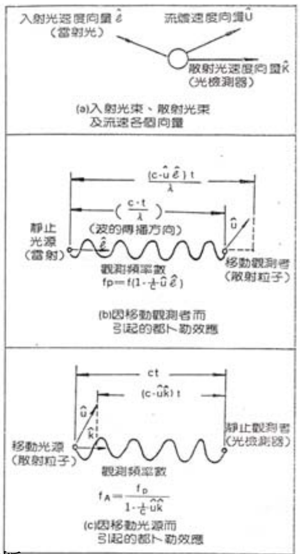

圖1. 都卜勒效應。
(a)入射光束、散射光束及流速各個向量
(b)因移動觀測者而引起的都卜勒效應
(c)因移動光源而引起的都卜勒效應

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- LDV (TSI) dual beam

– Intensity measured by a photodetector

$$A = A_1\cos(2\pi f_1 t + \phi_1)$$
$$A' = A_2\cos(2\pi f_2 t + \phi_2)$$
$$I = B(A + A')^2$$
$$\rightarrow I = B\left\{\begin{array}{l}\frac{1}{2}\left(A_1^2 + A_2^2\right) + \\ A_1 A_2 \cos\left[2\pi\left(f_1 - f_2\right)t + \left(\phi_1 - \phi_2\right)\right]\end{array}\right\}$$

– Set $\phi_1 - \phi_2 = 0 \rightarrow$ Optical Heterodyning (光外差檢測法)

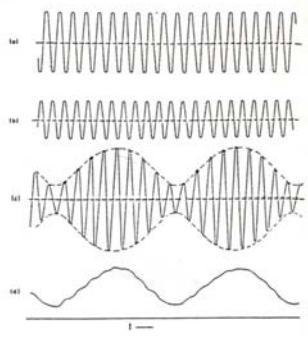

圖2. 兩個頻率的外差，訊號(a)與(b)相加形成脈波(c)，經過整流後成為拍訊號(d)。

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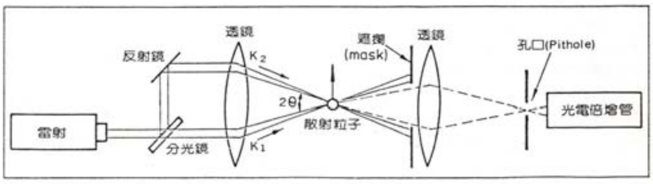

圖3. 雙光束干涉型雷射測速儀。

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– Doppler frequency

$$f_D = f_1 - f_2 = \frac{f\left[\left(1 - \mathbf{u}\cdot\mathbf{l}_1/c\right) - \left(1 - \mathbf{u}\cdot\mathbf{l}_2/c\right)\right]}{1 - \mathbf{u}\cdot\mathbf{k}/c}$$

$$\xrightarrow{u<<c} f_D = \frac{f\mathbf{u}\cdot\left(\mathbf{l}_2 - \mathbf{l}_1\right)}{c} = \frac{2|\mathbf{u}|\sin\theta}{\lambda}$$

– Pros & cons: independent of **k**, capable of receiving scattered light beam in any direction, large receiver diameter to get clear signal; finite measuring volume for sufficient fringes, no two particles simultaneously and hence low particle concentration.

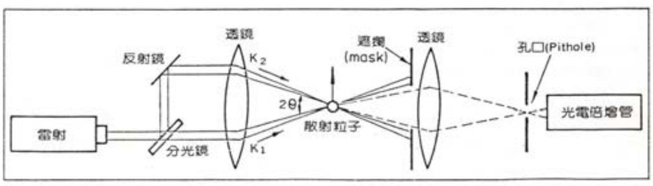

圖3. 雙光束干涉型雷射測速儀。

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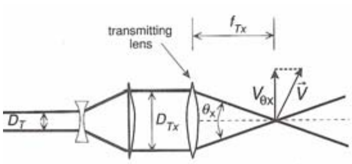
- Beam expansion

– to reduce the size of the measuring volume

– improve spatial resolution of velocity measurement and amplitude resolution (light power density↑)

– beam diameter $d_{ex} = E_x d_e$, *beam expansion ratio* $E_x > 1$

$$d_{fex} = \frac{d_{fe}}{E_x} \cong \frac{4 f_T \lambda}{\pi d_{ex}}$$



Photocopied from Tavoularis (2005)

- Frequency shifting

$$V_f = \Delta \nu \delta$$

$$V_\theta = (\nu_D^{'} - \Delta \nu)\delta$$

– *Bragg cell*: acousto-optic device

– for judgment of flow direction

- Multicomponent and multipoint systems

– Two-component system: two pairs of beams (simply three beams)

– *Two-color LDV*: two lasers or single with multiple spectral peaks, e.g. Ar-ion laser with λ of 514.5 and 488 nm; measurements of joint statistical properties such as covariance (Reynolds shear stress) …

– Three-component system (another λ of 476.5 nm or from a different type of laser): coordinate transformation may be needed.

– Multipoint measurement: spatial correlations and wavenumber spectra in different directions; usually two LDV systems at most …

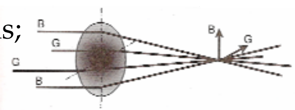


Figure 11.14. Sketch of a two-component LDV configuration with two pairs of beams at orthogonal planes; the letters G and B indicate beams with light at the green and the blue spectral peaks of an Ar-ion laser, as well as the corresponding measured velocity components.

Photocopied from Tavoularis (2005)

• Doppler signal

– *pedestal*: Gaussian distribution of light intensity

– *burst*: fringe crossing by particles in the measuring volume with amplitude modulated oscillatory function of ν'_D

– burst signal ~ size and refractive index of particles, position, path

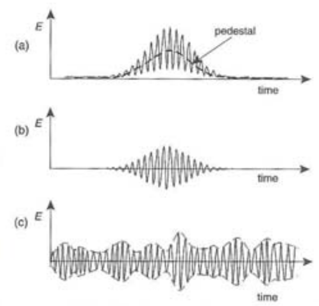


Figure 11.13. Typical Doppler signals (a) of a single particle, (b) of a single particle with the pedestal removed, and (c) of multiple particles with the pedestal removed.

Photocopied from Tavoularis (2005)

– accuracy (high burst density) ~ *ambiguity noise* and *phase noise*

• Other types

– *reference beam*

– *two-scattered beam*

▪ An example: TSI LDV dual-beam system

• Doppler shift of light frequency

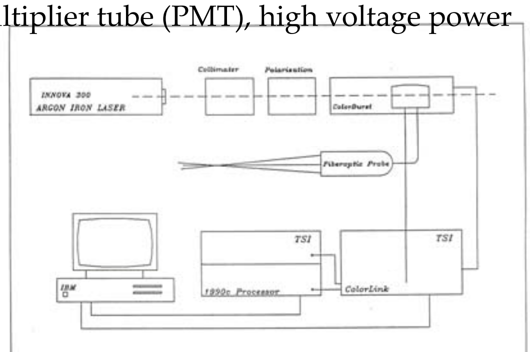
– Beam source: laser, collimator, polarization (for beam splitter)

– Color Burst: Bragg cell (frequency), dispersion prism (color)

– Color Link: photomultiplier tube (PMT), high voltage power supply, frequency shifter, A/O oscillator

– 1990c processor

– FIND software



陳建安繪 (1994)

C.A.Chen

PDPA for Particle Measurement

- Acronym: phase Doppler particle analyzer (PDPA or PDA)
- Simultaneous measurement of flow velocity and size distribution
  - Mie scattering: light reflected or refracted through → phase shift
  - Determine phase shifts between Doppler signals of different detectors + geometrical arrangement, λ, optical parameters → D
- Pros and cons
  - Irrelevant to multiple scattering and absorption

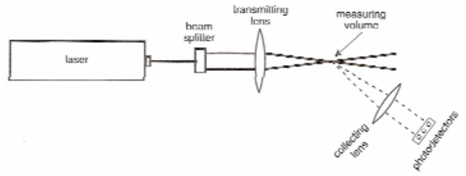


Figure 13.6. Sketch of a phase Doppler particle analyser.

  - Single particle in measuring volume → low concentration
  - Suitable only for optically homogeneous, spherical particles

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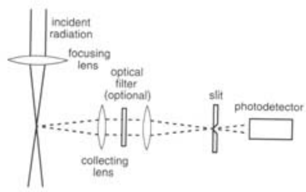
Measurement of Temperature and Species Concentration

- Background
  - Quantum mechanics/atomic & molecular physics
  - Elastic/inelastic scattering/absorption/nonlinear optical process
- Light-scattering method
  - Small measuring volume $\lesssim 1\ mm^3$
  - Spatial filter using a slit or pinhole



  - Right-angle collection but not line-of-sight methods (~ in situ absorption and emission spectroscopy): local but not path-average
  - Planar light-scattering methods

Photocopied from Tavoularis (2005)

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- Mie scattering
  - Elastic scattering of light quanta from particulate matter
  - Basic effect underlying particle sizing, LDV, differential absorption backscattering ~ local concentration of particles
  - Accuracy affected by particle size (polydispersity), refractive index, particle coagulation, and absorption; not specific to species
- Molecular radiation emission
  - Radiation scattering at the molecular level
  - Identification of species and concentration
  - $I_{nm} = A_{nm} N_n h \nu_{nm}$, where A_{nm} is *Einstein transition probability*
  - High-power radiation sources and careful experimental setting

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- Rayleigh scattering
  - Elastic scattering from isolated atoms and ordinary molecules: $D/\lambda \ll 1$ (< 1/15) ~ limit of Mie scattering
  - Sky colors ← *Rayleigh scattering cross section* $\sigma_R = \sigma_T (\lambda_0/\lambda)^4$ where *Thomson-scattering cross section* for a single electron σ_T = 6.65×10^{-29} m^2, and λ_0 the characteristic wavelength of an atom
  - Interfered by Mie scattering ~ clean condition, strong signal …
  - Not specific to species; continuous signal, temporal resolution
  - Measurement for total density, temperature (const. P, spectra)
  - Different from Mie scattering in which many atoms/molecules gather and EM waves interfere (no lateral scattering, directional)

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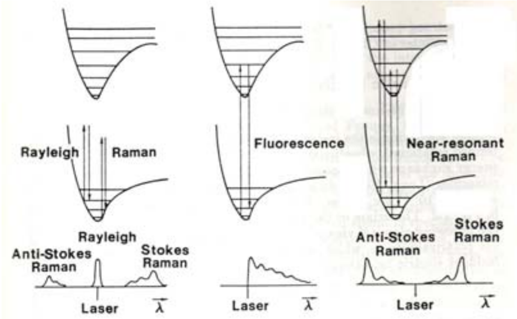

Figure 1.2: Incoherent light scattering processes and spectra. Two molecular electronic energy states with vibrational energy levels are shown. Rotational energy level substructure within the vibrational levels is not shown. Increasing energy is vertically upward. The electronic states are indicated by displaying the potential energy as a function of internuclear separation.

Photocopied sources
Top: Eckbreth (1988)
Bottom: Tavoularis (2005)

$$\sigma_\lambda = \frac{\lambda_F^2}{8\pi^2}\begin{bmatrix} i_1(x, n_P/n_F, \theta) \\ + i_2(x, n_P/n_F, \theta) \end{bmatrix}$$

$$x = \pi D_P/\lambda_F, \lambda_F = \lambda/n_F$$

$$\Phi_\Omega = I_0 \int_\Omega \sigma_\lambda d\Omega$$

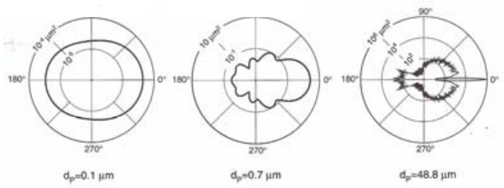

Figure 5.13. Monochromatic scattering cross sections of glass spheres in air, according to Mie-scattering theory; λ = 0.488 μm. Note that the radial axis is logarithmic, representing changes of orders of magnitude in values.

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- Raman scattering
  - *Spontaneous Raman* effect (~ 10^{-14} – 10^{-12} s)

  – Measurement of temperature, species and concentration

  – Unique vibrational energy levels, not contaminated by incident light, detection for different molecules; low intensity (10^{-5} – 10^{-2} lower than RS)

  – As T↑, vibrational/rotational energy bands↑ → spectral overlapping

  – High-power (e.g. KrF excimer) laser; low λ preferred, $\sigma \propto \lambda^{-4}$

  - *Near-resonant Raman* scattering (cross section enhanced by 6 orders)

  – Frequency tuned near (off) an electronic resonance of molecule, insensitive to collisional quenching

  - *Stokes transition*: photon emitted at higher energy than absorbed one
  - *Anti-Stokes transition*: photon emitted at lower energy than absorbed

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- Origin in terms of dipole moment and polarizability $\vec{p} = \alpha \varepsilon_0 \vec{E}$

$$\alpha = \alpha_0 + \left(\frac{\partial \alpha}{\partial Q}\right)_0 Q \qquad Q = Q_0 \cos \omega_v t \qquad \text{e.g., in vibrational mode}$$

$$\rightarrow \vec{p} = \left[\alpha_0 + \left(\frac{\partial \alpha}{\partial Q}\right)_0 Q_0 \cos \omega_v t\right] \varepsilon_0 \vec{E}_0 \cos \omega_0 t$$

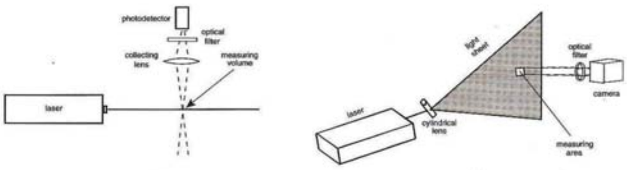
$$= \alpha_0 \varepsilon_0 \vec{E}_0 \cos \omega_0 t + \left(\frac{\partial \alpha}{\partial Q}\right)_0 \varepsilon_0 \frac{Q_0 \vec{E}_0}{2} \left[\cos(\omega_0 - \omega_v)t + \cos(\omega_0 + \omega_v)t\right]$$

- Indicating Rayleigh process, Stokes transition, anti-Stokes transition
- Raman: species specific and linearly proportional to number density

▪ CARS (coherent anti-Stokes Raman spectroscopy)

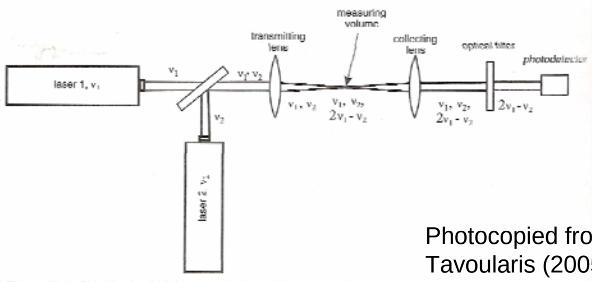
- much stronger signal, not sensitive to soot
- two monochromatic beams (by one tunable, one fixed laser) ν_1, ν_2 ($< \nu_1$)
- molecules with vibrational energy $\Delta\nu = \nu_1 - \nu_2$ → coherent, collinear

beams $\nu_1 + \Delta\nu$ (anti-Stokes) and $\nu_2 - \Delta\nu$ (Stokes)



(a) (b)

Figure 13.5. Sketches of optical arrangements for (a) local LIF and (b) PLIF.



Photocopied from Tavoularis (2005)

Figure 13.4. Sketch of a CARS system (adapted from Ref. 50).

• CARS: anti-Stokes region free of fluorescent interference

• More complicated spectra, limited sensitivity to species concentration

• At atmospheric pressure, CARS is restricted to major constituents, sensitivity capabilities similar to SRS; both are complimentary to LIFS which is capable of detecting flame radicals at trace, ppm, levels but not for major species due to spectral inaccessibility of electronic transitions

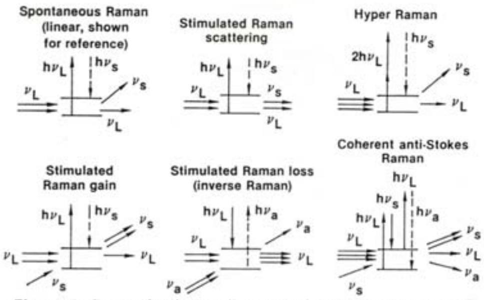


Figure 1.3: Survey of various nonlinear optical processes. Two different ro-vibrational states are shown. Upward facing arrows indicate photon absorption or conversion; downward facing arrows depict photon emission.

Photocopied from Eckbreth (1988)

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▪ Fluorescence

• *Fluorescence*: time delay after absorption ~ 10^{-10} – 10^{-5} s; transition between the same electronic spin states (multiplicity)

• *Phosphorescence*: time delay ~ 10^{-4} s – hours; transition between different electronic spin states

• An uncertainty – *quenching* in fluorescence: with sufficient time for collisions of molecules to occur and photon energy to be converted to chemical reaction, dissociation, and ionization energies, before emission

• Other causes to fluorescence in addition to photon absorption: electron bombardment, heating/chemical reaction (*chemiluminescence*)

• Resonant/non-resonant(shifted) fluorescence: latter preferred, to allow isolation of fluorescence radiation from incident light & Mie scattering

• High intensity, independent of direction, randomly polarized

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- Laser-induced fluorescence spectroscopy (LIF/LIFS)

– Principal measurement of concentration in liquid and gas

– For *T*: fluorescence quantum efficiency↓ with *T*↑ (~linearly)

– Type: local LIF vs. planar LIF (PLIF)

– Qualitative and quantitative (limited by depletion, extinction, *T* sensitivity, pH sensitivity, spatial resolution, non-uniform illumination)

– Use passive fluorescent seeding materials in non-reacting gases such as biacetyl which emits radiation in visible range

– Mostly used in flames, with fluorescence given by radicals such as OH, CH, CO, and NO → map chemical reactions

– Produce strongest radiation signal from a single species

– Excited by tunable, pulsed, dye and excimer lasers, visible/ultraviolet

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A Case Study of Measuring Velocity and Species Concentration

- A study of bluff-body combustion field
  - Background
  - Experimental facility
- Measurements
  - Visual observation
  - Flow velocity field by LDV
  - Distribution of OH radicals by PLIF

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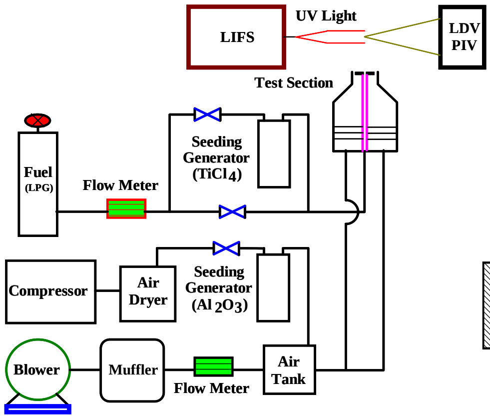
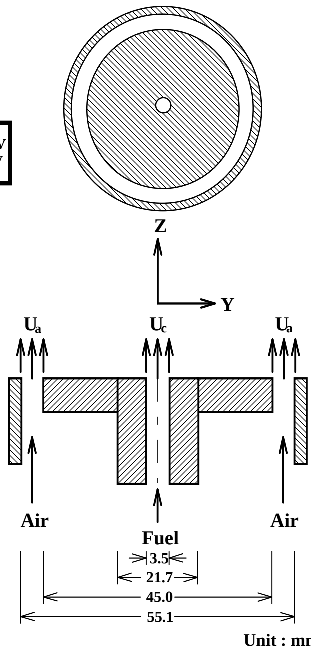
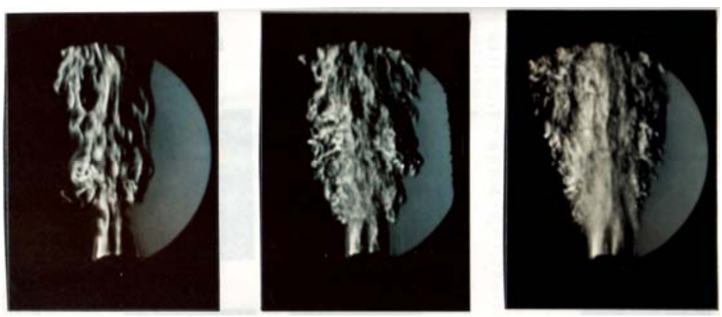




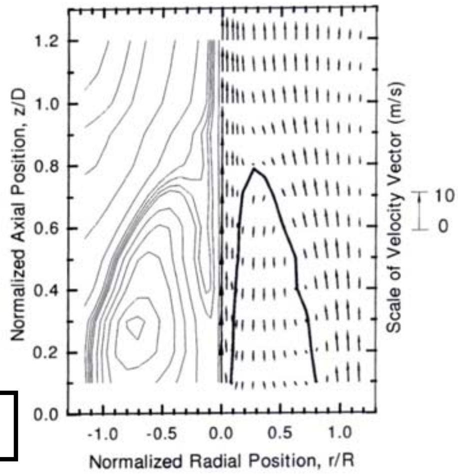
Photocopied from Yang et al., *Combust. Sci. Tech*. (2002)

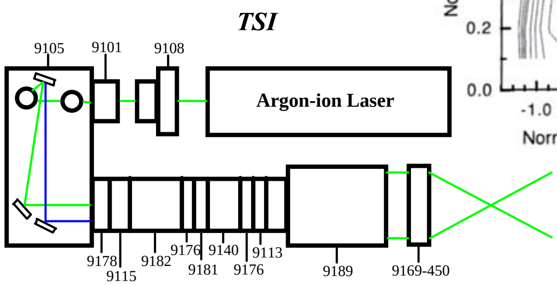
Top: Yang et al. *Combust. Sci. Tech.* (2002)
Bottom: Pan, MS thesis (1996)



LDV arrangement and measurement

Photocopied from Yang et al., *Combust. Sci. Tech*. (2002)





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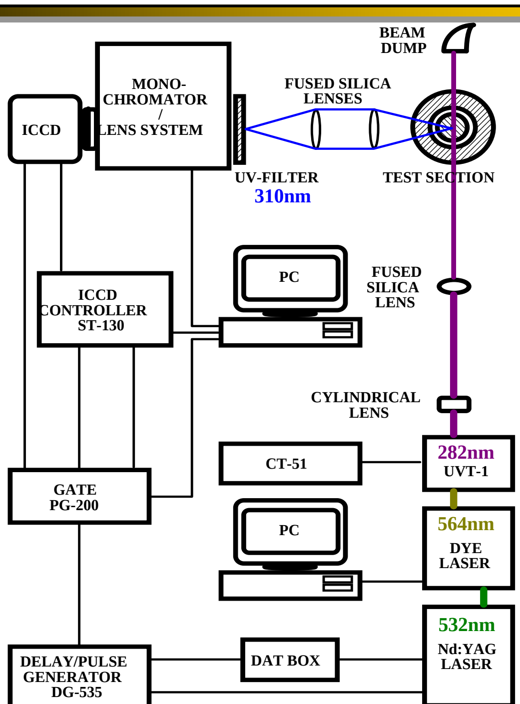

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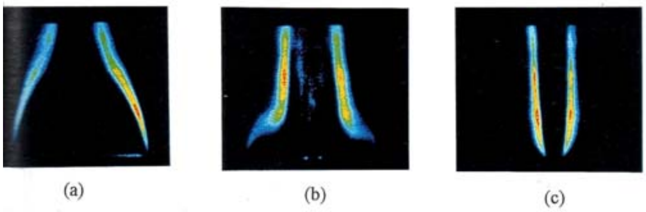
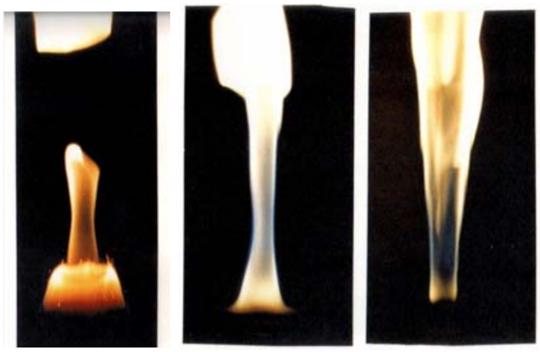
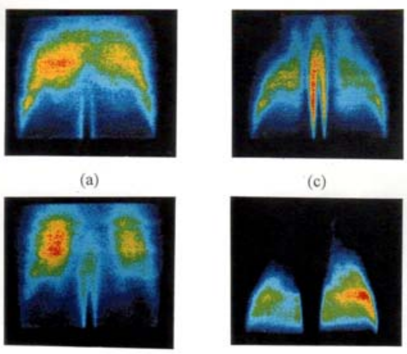
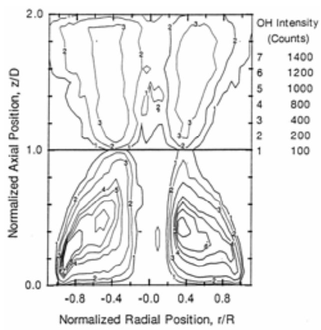
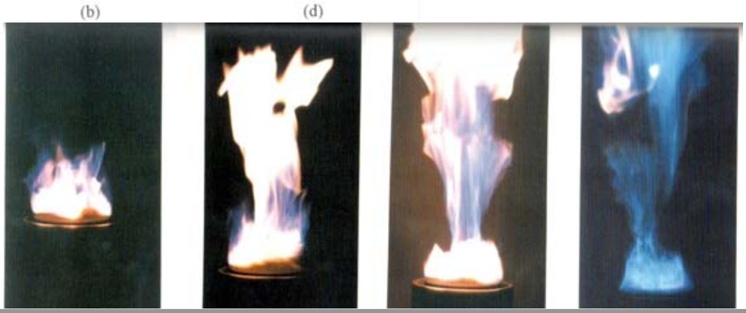


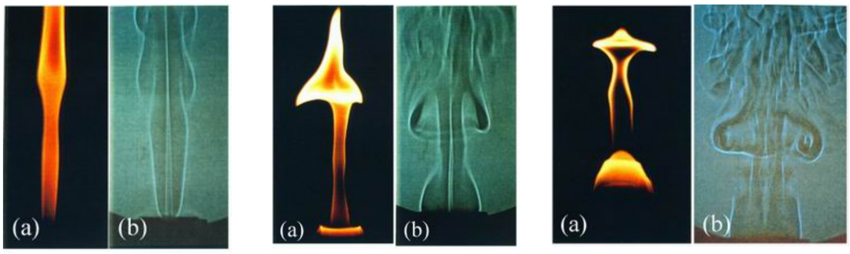


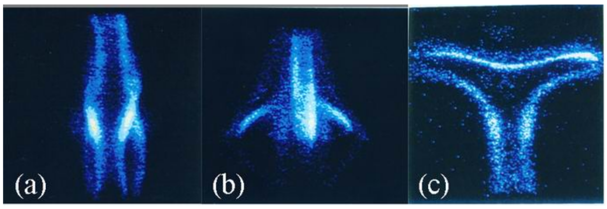
Pan, MS thesis (1996)











Pan, MS thesis (1996); also Pan et al., *Combust. Sci. Tech.* (2009)

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