November 2004

Molecular Sensing based on the Nonlinear Optics with Metal Nano-Grating

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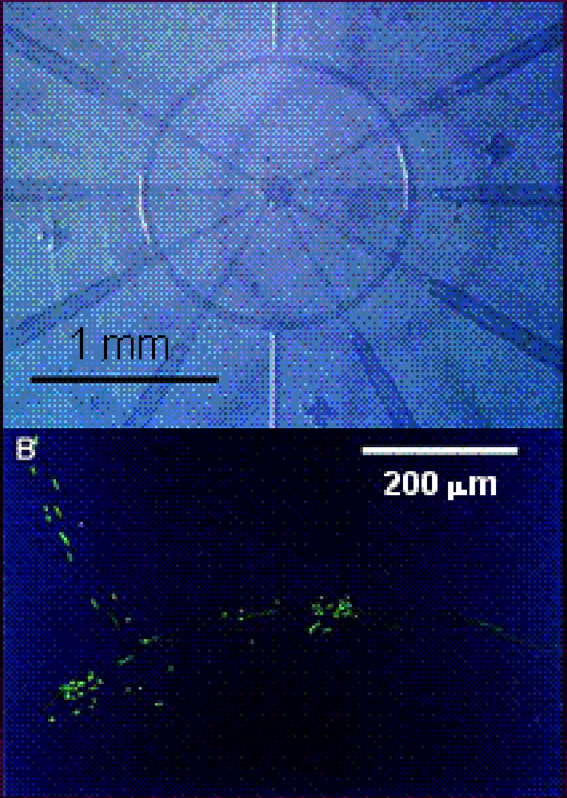
Collaboration: Z. Zhang, T. D. Neal, D. T. Wei, and A. Scherer

Acknowledgements: M. Terazima (Kyoto University)

Micro (Nano) fluidic devices

Recently, micro and nano fluidic devices have been developed and used to wide application fields

In many cases, fluorescent beads, dye molecules, or colored solution were used as the host in such fluidic devices.

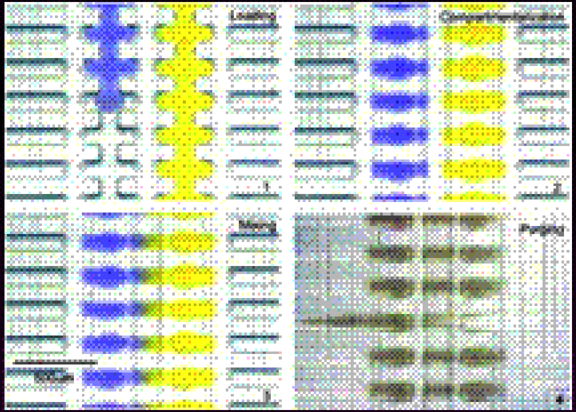


Fluorescent latex beads

SR. Quake and A. Scherer, Science, 290, 5496 (2000)

DNA with fluorescent dyes

SR. Quake et al, Biophysical Journal, 82, 2480 (2002)



Colored solution

T. Thorsen et al, Science, 298, 580 (2002)

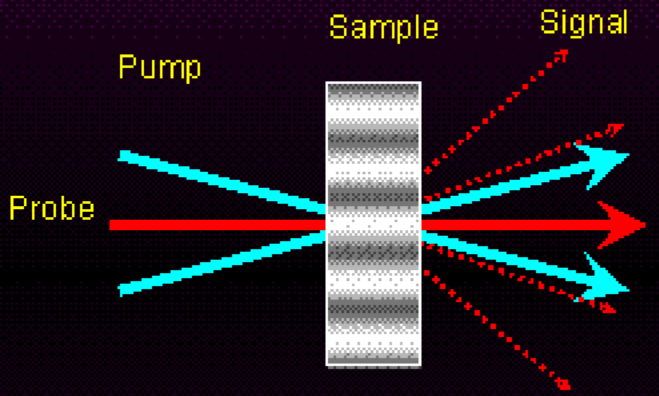
Many molecules and chemical compounds have neither no fluorescence nor no color

High sensitive molecular detection technique without light emission is necessary for wider application of such micro and nano fluidic devices

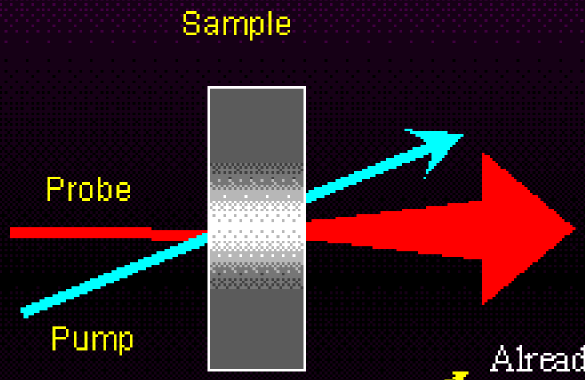
Nonlinear Optical Effect

$$P / \varepsilon_0 = \Sigma\, \chi_{ij}^{(1)} E_j + \Sigma\Sigma\, \chi_{ijk}^{(2)} E_j E_k + \Sigma\Sigma\Sigma\, \chi_{ijkl}^{(3)} E_j E_k E_l + \ldots$$

$$E_{\mathrm{signal}}(t) = \chi^{(3)}(t) E_{\mathrm{probe}} E_{\mathrm{pump}} E_{\mathrm{pump}}$$



Transient Grating



Transient Lens

Already applied to micro fluidic device

Tokeshi M, Minagawa T, Kitamori T, Analytical chemistry, 72, 1711 (2000)

femto → pico → micro → milli → second → min → hour → **Time**

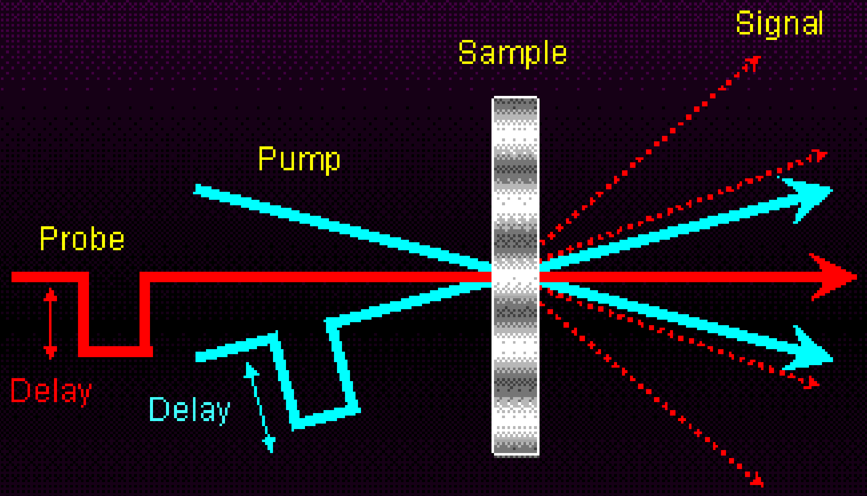
- Electronic polarization
- Electron transfer
- Energy transfer
- Carrier Dynamics
- Excitation Dynamics
- Molecular vibration

- Thermal dynamics
- Volume, structure change
- Density change
- Ultrasonic, Acoustic wave
- Chemical reaction
- Molecular translation

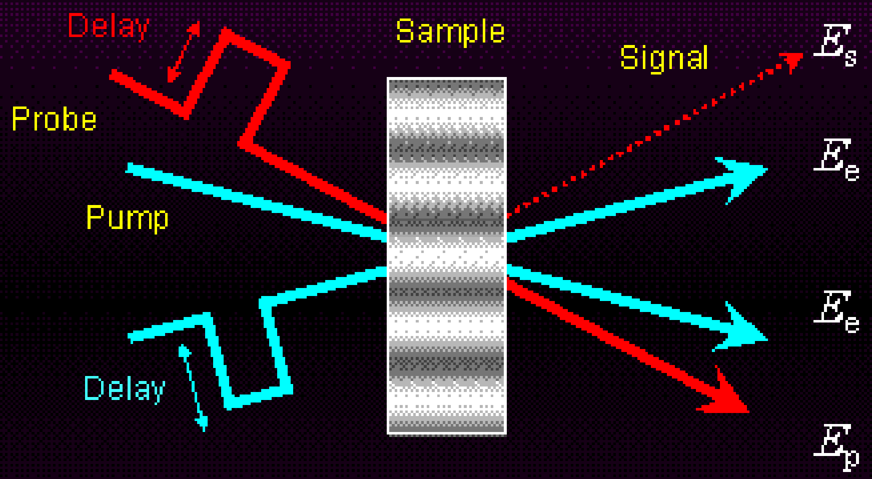
- Clustering, Aggregation
- Molecular harmonic effect
- Nano particle growth
- Crystal growth
- Phase Transfer
- Metal diffusion

Thin and Thick Grating

Transient Grating Technique



Thin Grating

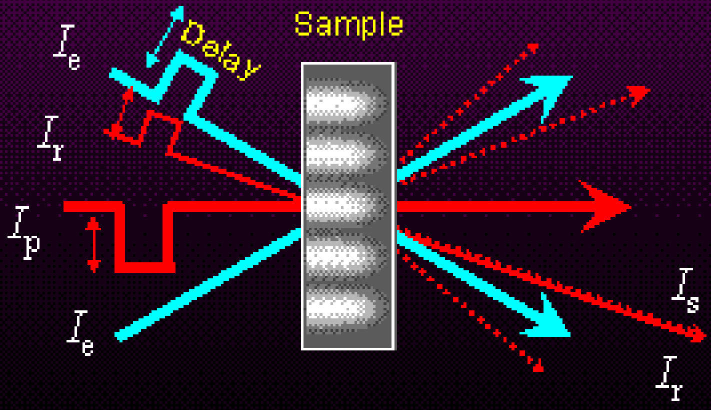


Thick Grating

$$P/\varepsilon_o = \Sigma\, \chi_{ij}^{(1)} E_j + \Sigma\Sigma\, \chi_{ijk}^{(2)} E_j E_k + \Sigma\Sigma\Sigma\, \chi_{ijkl}^{(3)} E_j E_k E_l + \ldots$$

$$E_s(t) = \chi^{(3)}(t) E_p E_x E_x$$

Optical Heterodyne Detection



Optical heterodyne detected TG (OHD-TG)

High sensitivity
Linear relationship

Four beams (two pump and two probe)

2 pump beams must be coherent
2 probe beams must be phase matched

$$I_{\text{total}}(t) = A\,|E_r + E_s(t)\,|^2$$

$$= A\,\{|E_r\,|^2 + E_r^*\,E_s(t) + E_s(t)\,E_r^* + |\,E_s(t)\,|^2\}$$

$$= \underbrace{I_r}_{\text{Offset signal}} + \underbrace{2a\,(\chi^{(3)\prime}(t)\,\cos\Delta\phi + \chi^{(3)\prime\prime}(t)\,\sin\Delta\phi\,)\,I_e\,I_p}_{\text{Heterodyne signal } I_s(t)} + \underbrace{|\,\chi^{(3)}\,(t)\,|^2\,I_e\,I_e\,I_p}_{\text{Usual homodyne signal}}$$

$$E_s\,(t) = \chi^{(3)}(t)E_pE_eE_e$$

$$E_r = a\,\mathrm{e}^{\,i\Delta\phi}\,E_p$$

$$|E_p| >> |E_s|$$

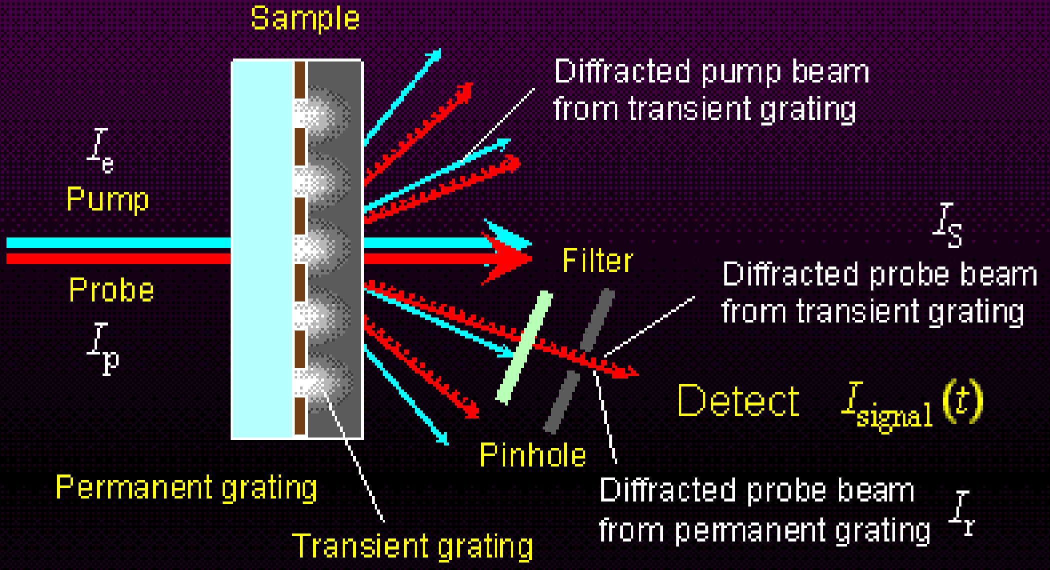
$$\boxed{I_s(t) \propto \chi^{(3)}{}'(t)\cos\Delta\phi + \chi^{(3)}{}''(t)\sin\Delta\phi}$$

Phase difference

Refractive index change $\delta n(t)$

Absorbance change $\delta k(t)$

Our New Technique



$$I_{signal}(t) = \underbrace{I_r}_{\text{Offset signal}} + \underbrace{2a\,(\chi^{(3)\prime}\cos\Delta\phi + \chi^{(3)\prime\prime}\sin\Delta\phi)\,I_e I_p}_{\text{Heterodyne signal}} + \underbrace{|\chi^{(3)}|^2 I_e I_e I_p}_{\text{Usual homodyne signal}}$$

Simple setup and alignment

High sensitivity

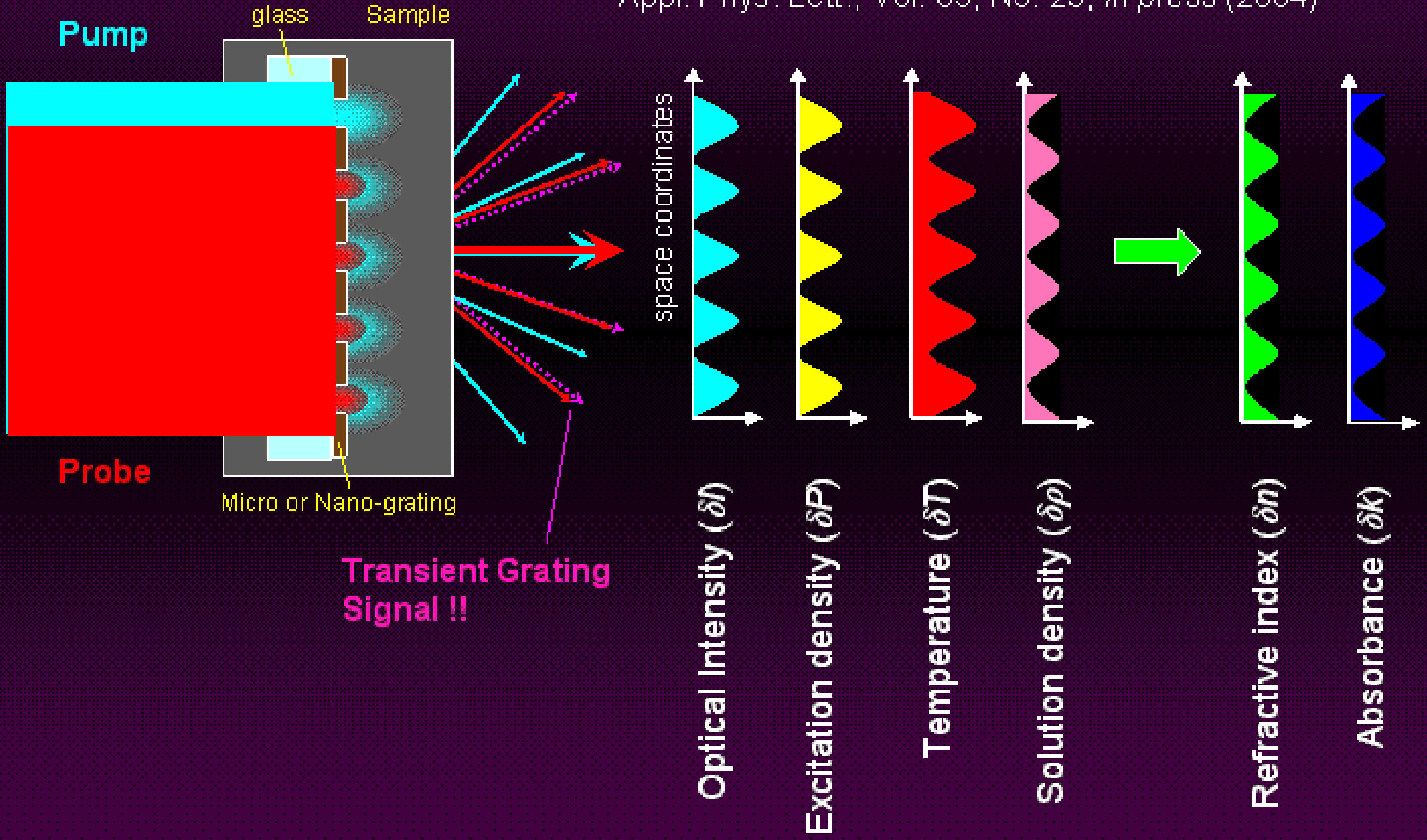
High S/N ratio

Linear relationship

Mechanism of Our Technique

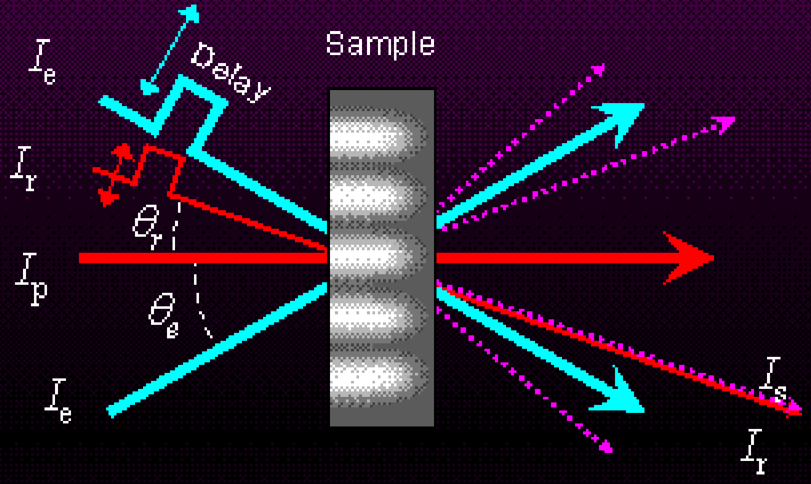
K. Okamoto, Z. Zhang, D. T. Wei, and A. Scherer

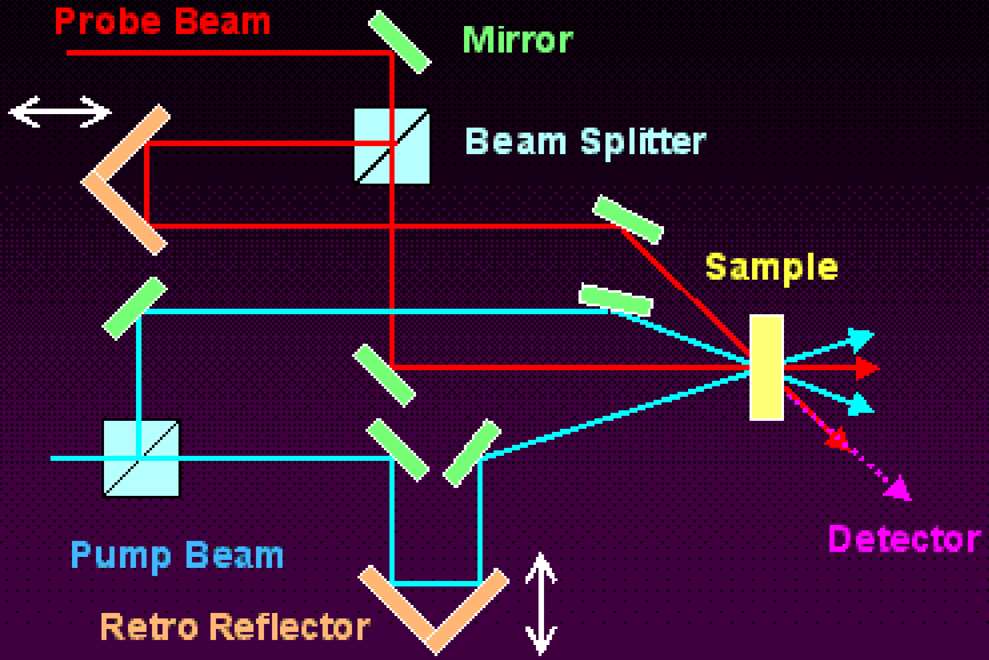
Appl. Phys. Lett., Vol. 85, No. 23, *in press* (2004)



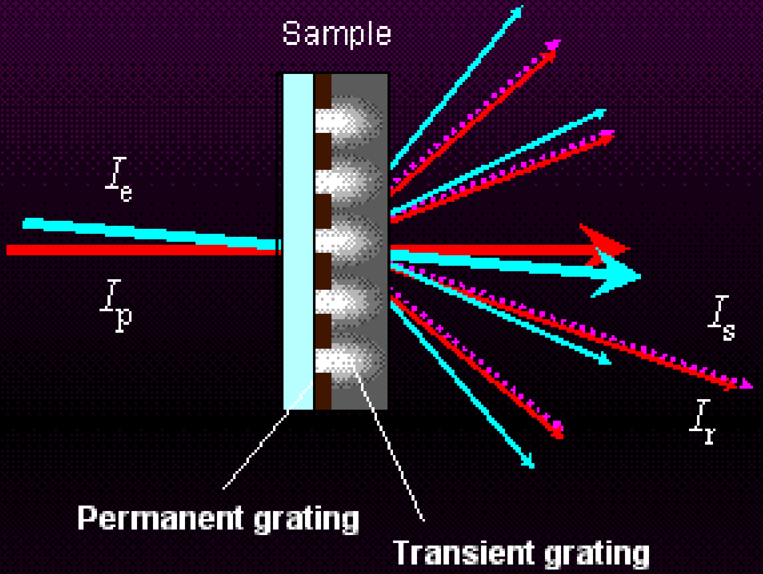
Optical alignment of Our Technique

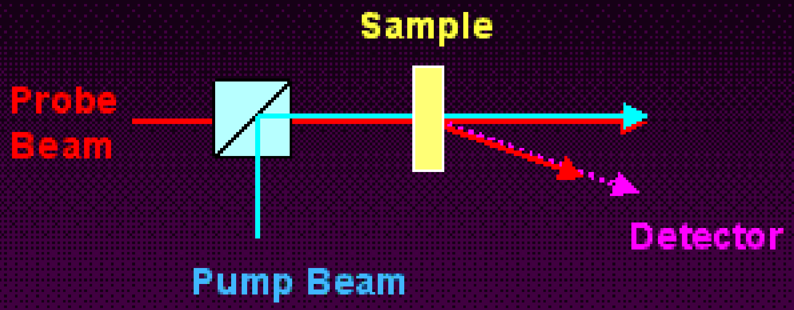
Previous method





Our New Method

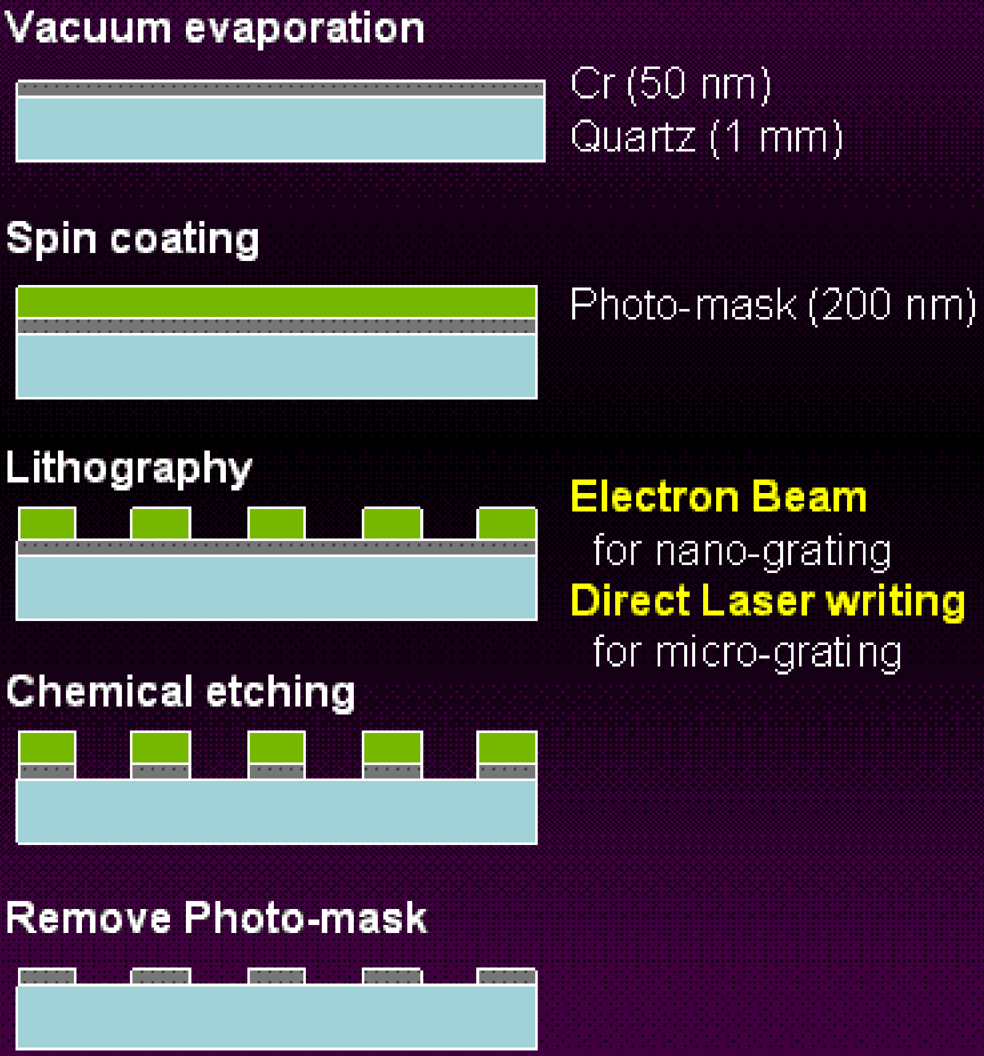




Very Simple and Easy !

Fabrication of the Metal Grating

© Koichi Okamoto



Vacuum evaporation

Cr (50 nm)
Quartz (1 mm)

Spin coating

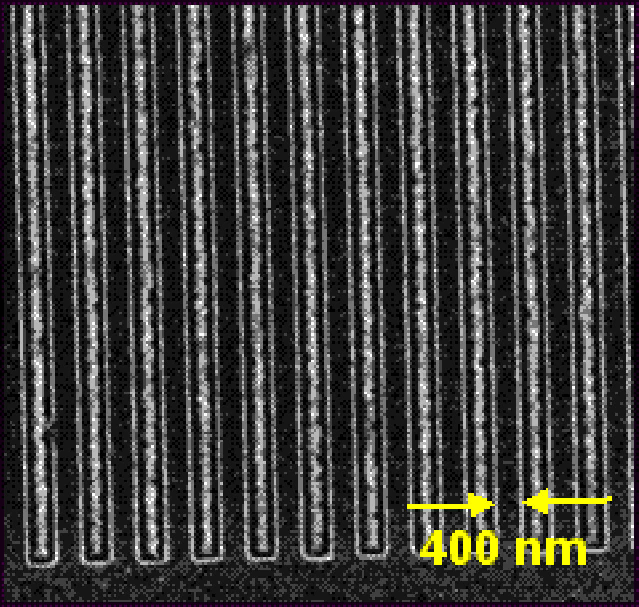
Photo-mask (200 nm)

Lithography

Electron Beam
for nano-grating
Direct Laser writing
for micro-grating

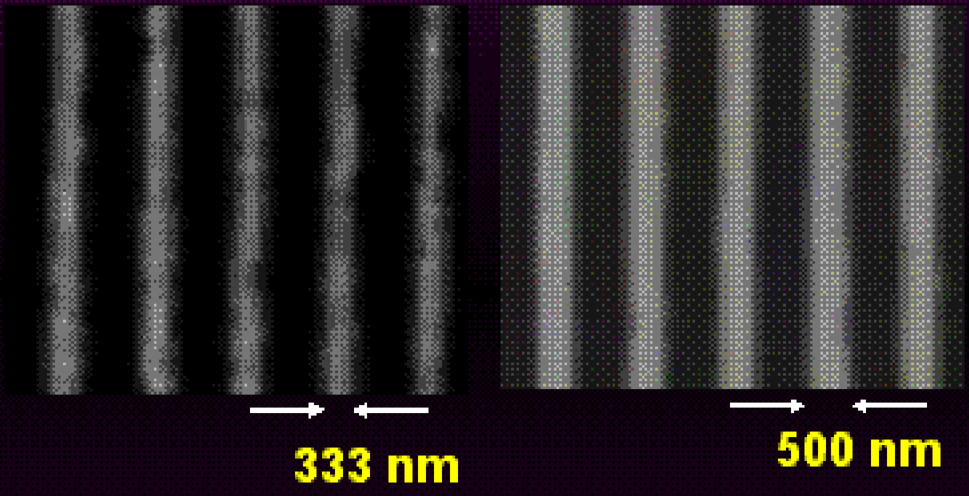
Chemical etching

Remove Photo-mask



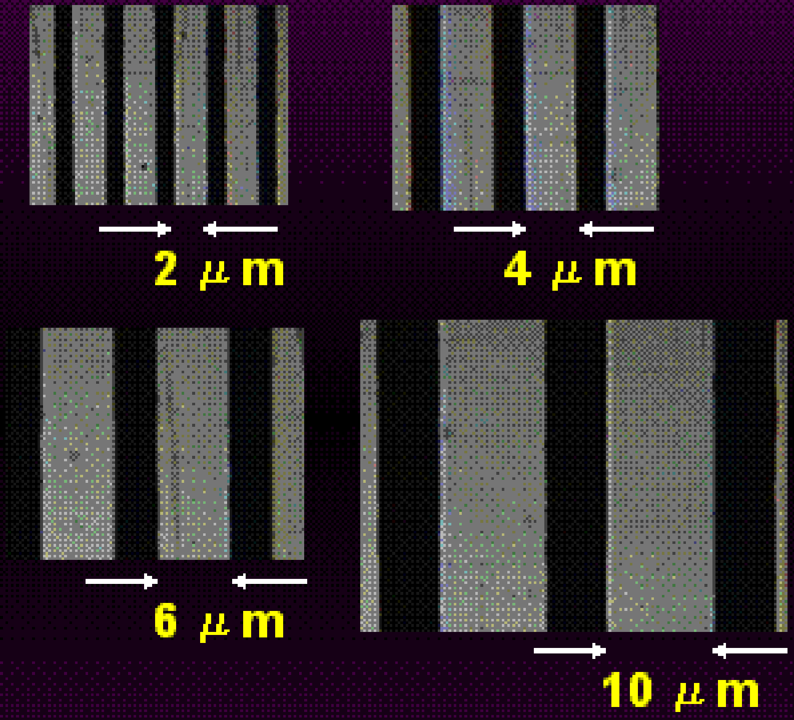
Scanning electron microscope (SEM) image of the smallest metal grating film (400 nm metal width and 1µm period).

Fabrication



Nano scale gratings

- Chromium evaporation on quartz substrates
- Patterned PMMA mask by **Electron Beam lithography**
- Chemical etching



Micron scale gratings

- Make photomask using **Direct Writing Laser lithography**
- Photolithography method to make micron grating on Mask Aligner
- Chemical etching

Sample Solution System

Sample solution:

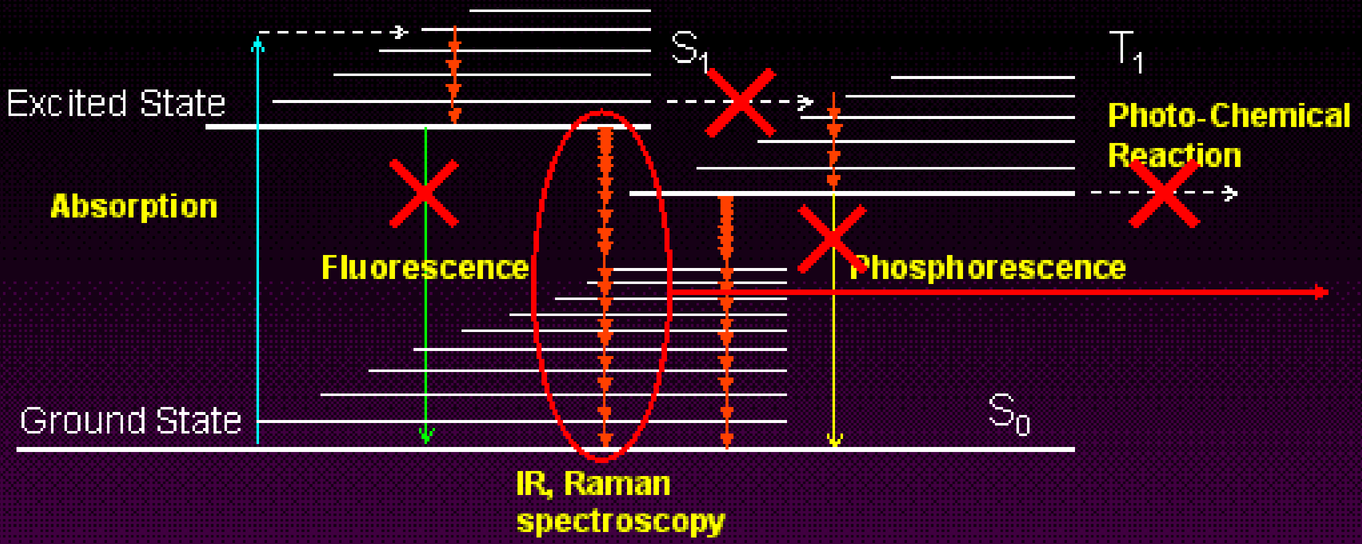
Nitrobenzene (5 vol. %)

In 2-prolanol

No color, No fluorescence

Photo-excited state is relaxed within very short time (~ps).

All absorbed photon-energy is converted into thermal energy (molecular heater)



Jablonskii diagram of molecule

Molecular Electron Excitation

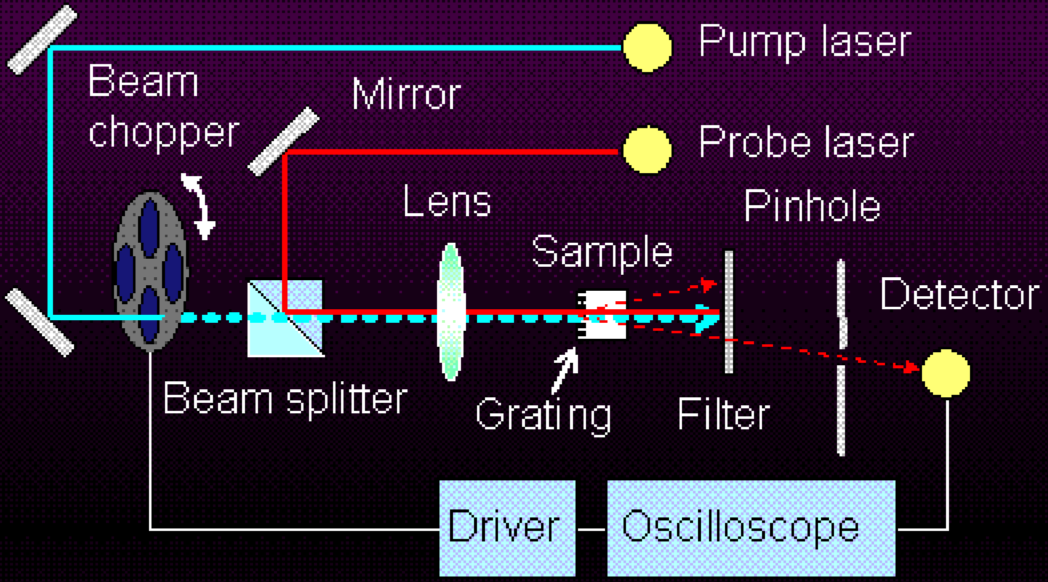
Molecular Vibration

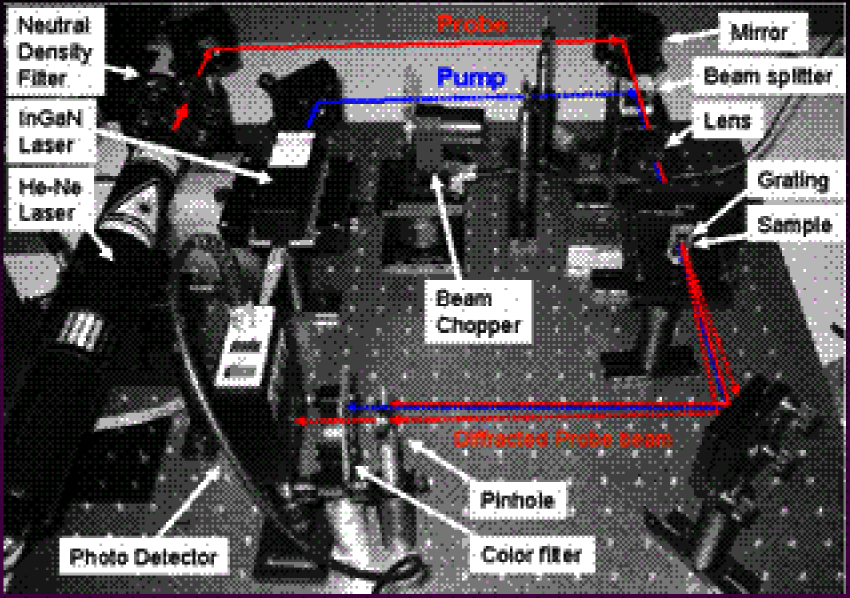
Molecular Translation

Temperature Increasing

Photothermal Process

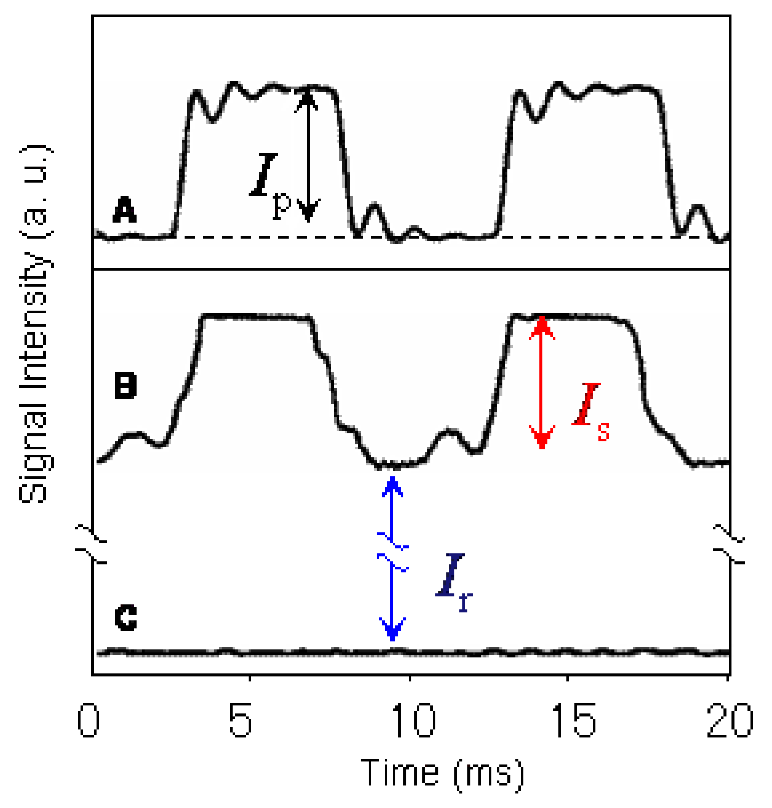
Setup with cw-Laser





Pump:	For cw measurement, Time-modulated (50 to 400 Hz) cw-InGaN laser (405 nm, 5 mW)
	For time-resolved measurement, frequency-tripled Nd:YAG laser (355nm, 10 ns, 0.3 mJ/pulse and 3 Hz)
Probe:	cw-He-Ne laser (633 nm, 0.05 mW)
Detector:	InGaAs-based avalanche photodetector

Diffracted Signal (cw)



$$I_{\text{signal}}(t) = I_r + b\chi^{(3)}{}'(t)\, I_e I_p$$

$$\chi^{(3)}{}'(t) = \delta n(t)$$

$$\delta n_{th}{}^{0} = \left[\left(\frac{\partial n}{\partial \rho}\right)_T \left(\frac{\partial \rho}{\partial T}\right) + \left(\frac{\partial n}{\partial T}\right)_\rho\right] \frac{Q}{\rho C_p} \times \alpha \Delta I[C]$$

n: reflective index, T: temperature, ρ: density of solution

$\delta n_{\text{th}}(t)$: reflective index change due to the thermal effect

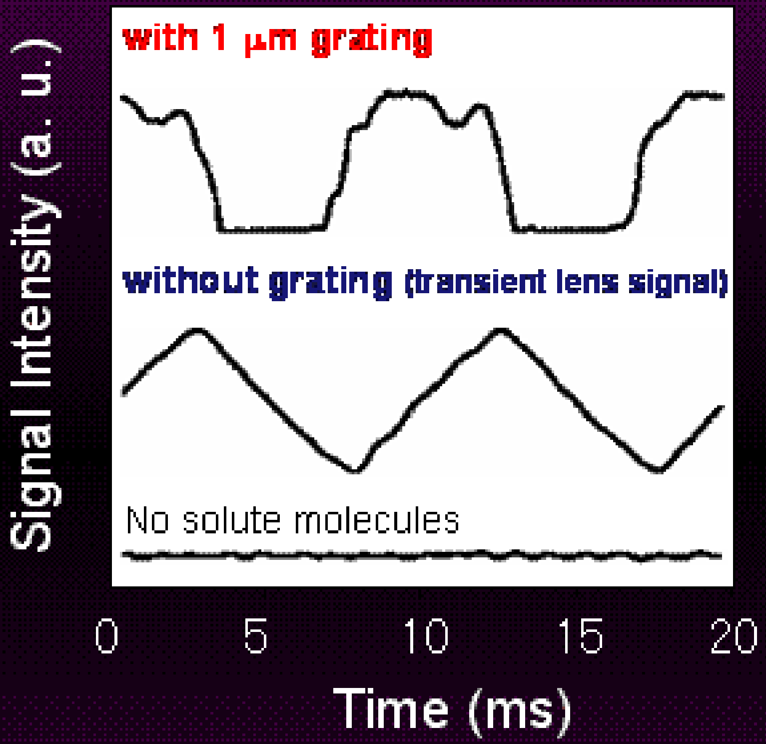
C_p:specific heat capacity, Q: released heat, α : constant

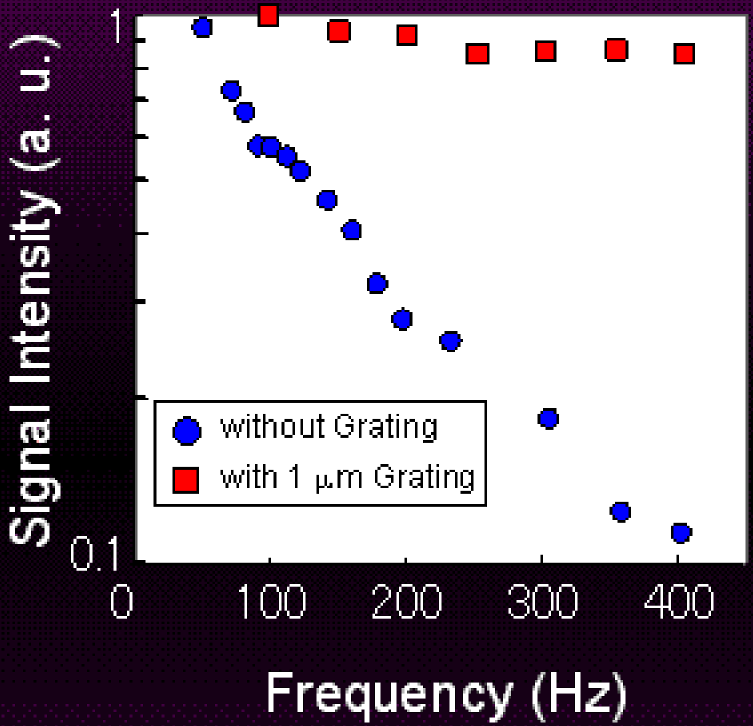
ΔI: absorbed light intensity,

[C]: molecular concentration

Time profiles of the pump beam (A) modulated by beam chopper, diffracted signal of nitrobenzene in 2-propanol (B) and only 2-propanol (C) with 1µm period's grating.

High frequency operation





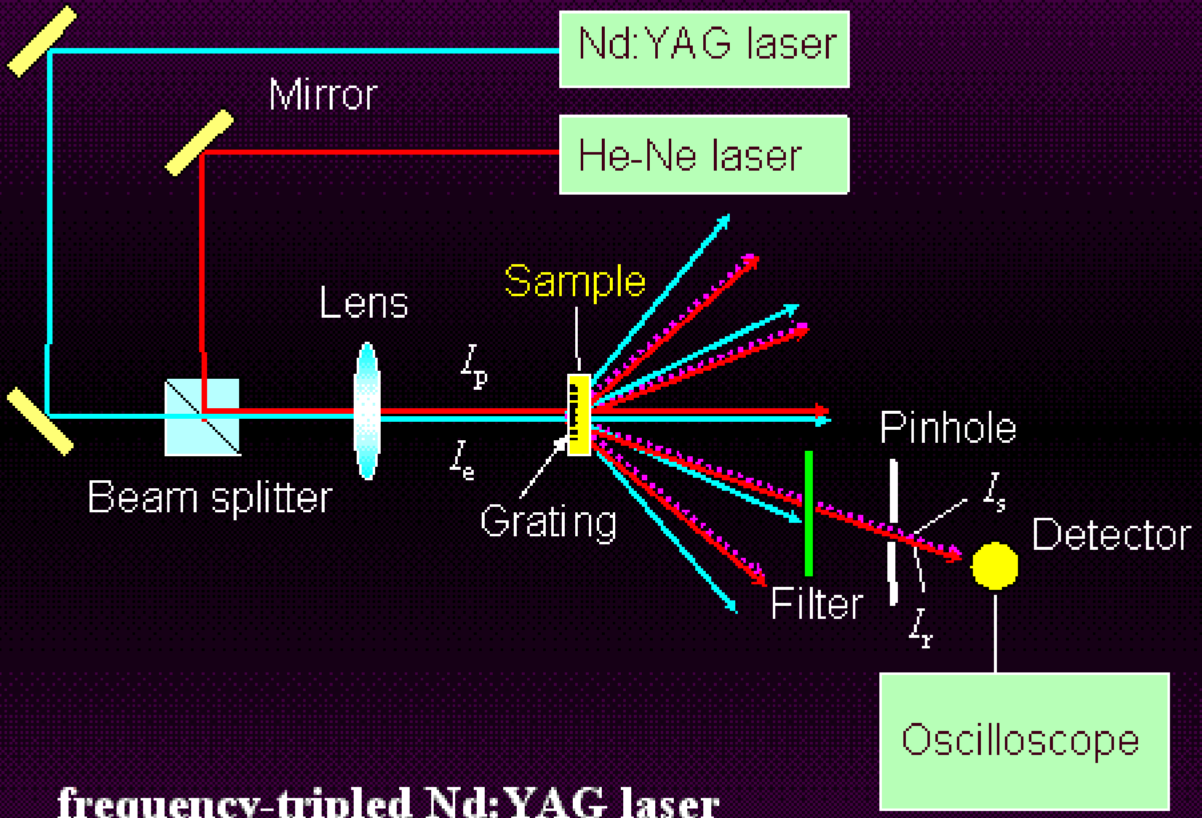
High speed (frequency) detection

High sensitivity

⇓

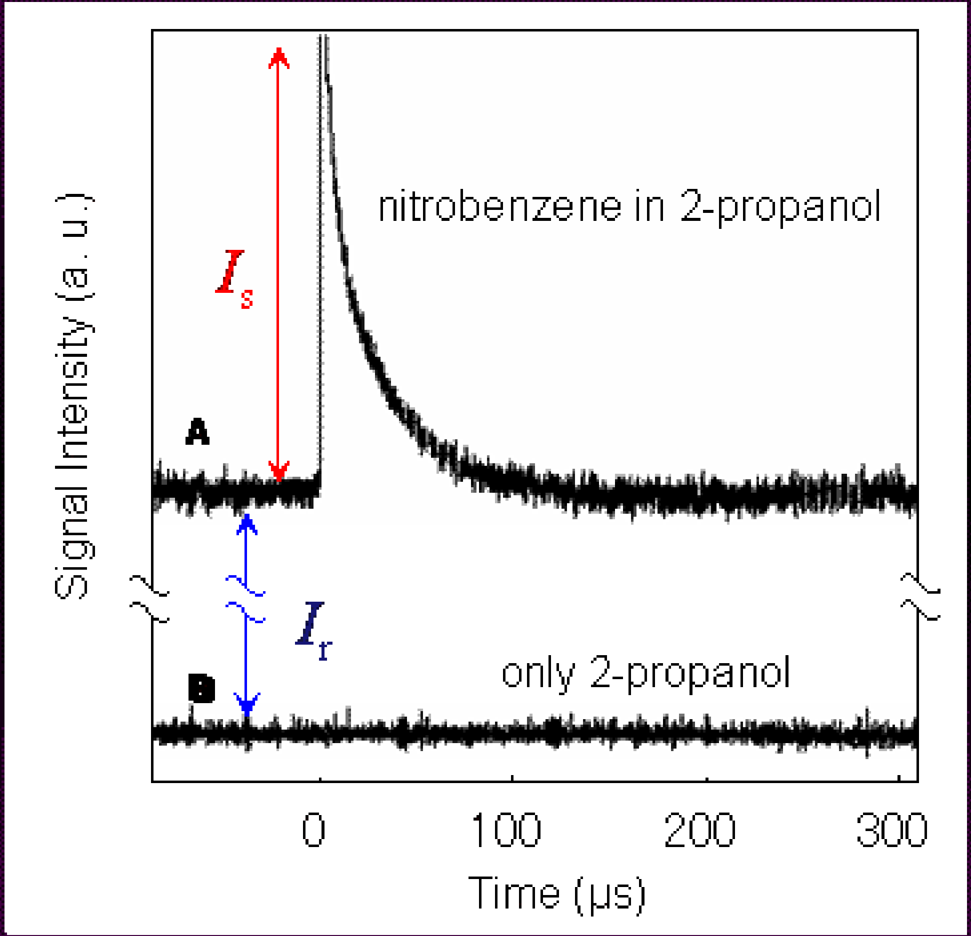
Well Applicable for molecular sensor in microfluidic devices

Setup with Pulse Laser



Pump:	**frequency-tripled Nd:YAG laser (355nm, 10 ns, 0.3 mJ/pulse and 3 Hz)**
Probe:	**cw-He-Ne laser (633 nm, 0.05 mW)**
Detector:	**InGaAs-based avalanche photodetector**

Time-Profile of the TG signal



$$I_s(t) \propto \delta n(t) \qquad \delta k(t) = 0$$

$$\delta n(t) = \left[\left(\frac{\partial n}{\partial \rho}\right)_T \frac{\partial \rho}{\partial T} + \left(\frac{\partial n}{\partial T}\right)_\rho\right]\delta T(t)$$

Diffusion rate equation,

$$\frac{\partial T(x,t)}{\partial T} = D_{th}\frac{\partial^2 T(x,t)}{\partial x^2} + \frac{Q(x,t)}{\rho C_p}$$

$$\delta T(t) = \delta T(0)\exp(-D_{th}q^2 t)$$

$$\left(q = \frac{2\pi}{\Lambda}\right)$$

Grating constant

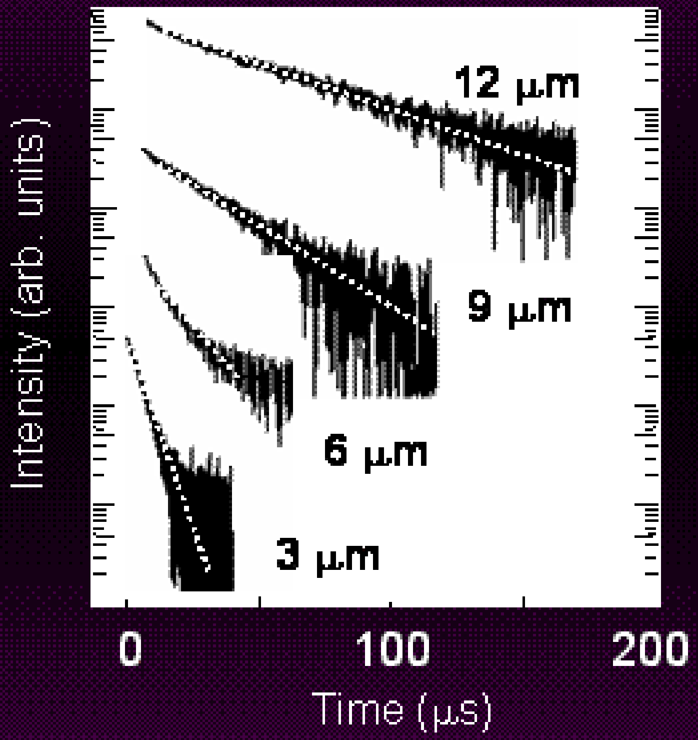
T: temperature,
ρ: density,
Q: heat energy

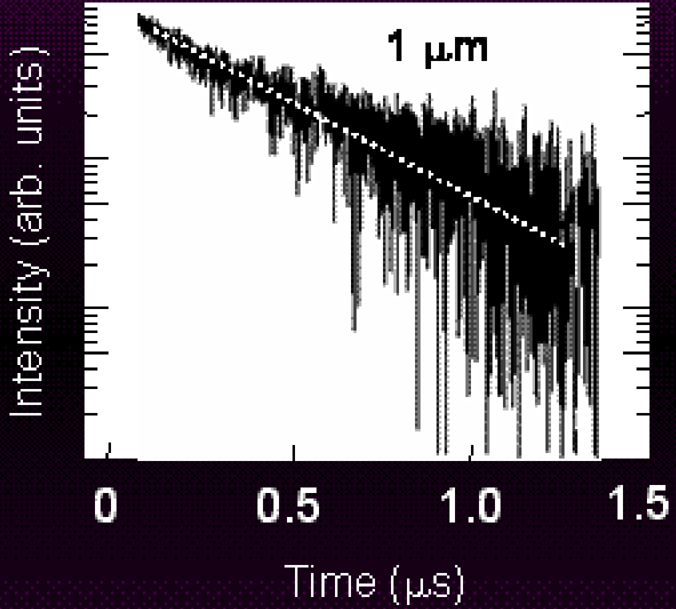
n: refractive index,
C_p: thermal capacity,
D_{th}: thermal diffusion coefficient

Fitting of the TG signals

© Koichi Okamoto

Time profile of the diffracted signals with metal grating of 12, 9, 6, 3 μm periods (a) and 1 μm period (b). Dashed lines were fitted by the exponential functions.





$$I_s(t) = I_s(0)\exp\left(-\frac{t}{\tau}\right)$$

Decay lifetime

Grating period

$$\underset{\text{Decay lifetime}}{\tau} = \frac{\overset{\text{Grating period}}{\Lambda^2}}{D_{th}4\pi^2}$$

Analysis of the time profiles

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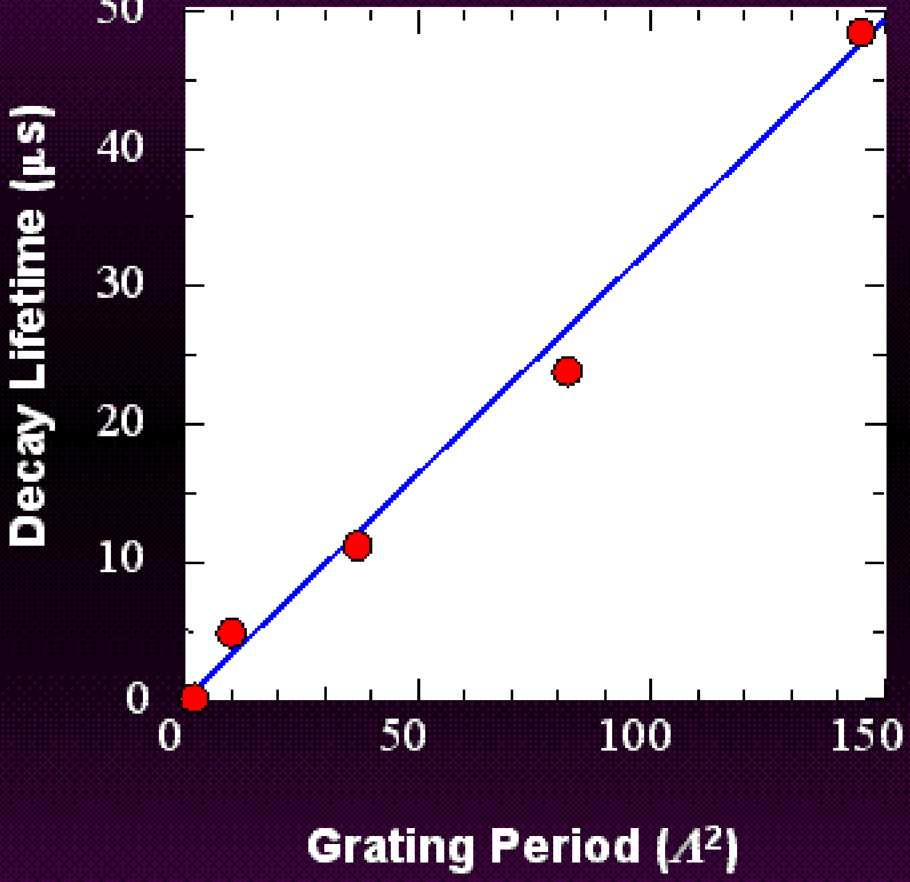

$$\tau = \frac{\Lambda^2}{D_{th} 4\pi^2}$$

Thermal diffusion coefficient (D_{th}) of 2-propanol

Experimental value

$D_{th} = 7.0 \pm 0.7 \times 10^{-8}\ m^2s^{-1}$

Calculated value $D_{th} = \kappa / C_p \rho$,
κ: heat conductivity, C_p:specific heat capacity,
ρ :density.

$D_{th} = 6.8 \times 10^{-8}\ m^2s^{-1}$

This technique is powerful tool for thermal dynamics sturdy in solutions.

Photochromic Molecule

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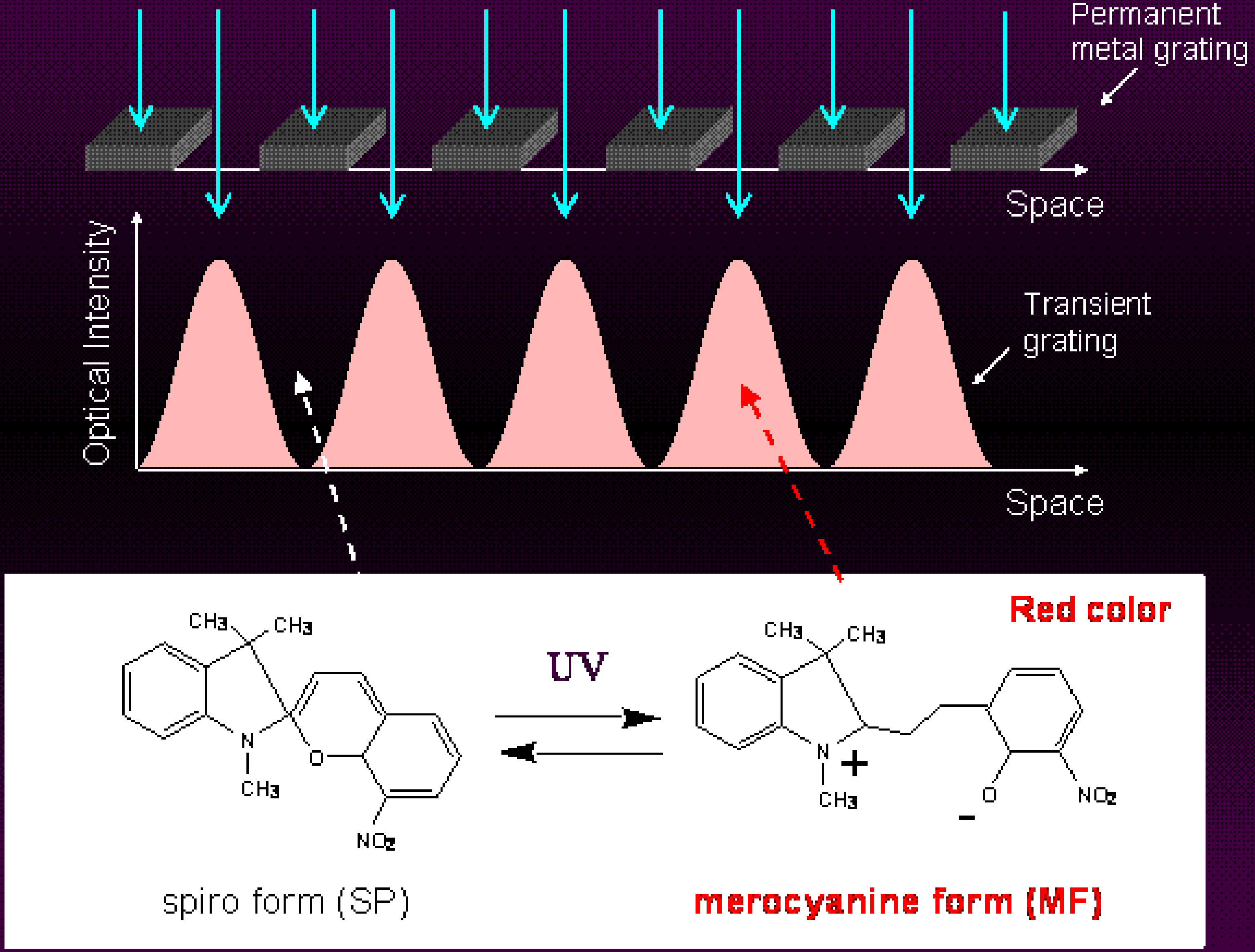
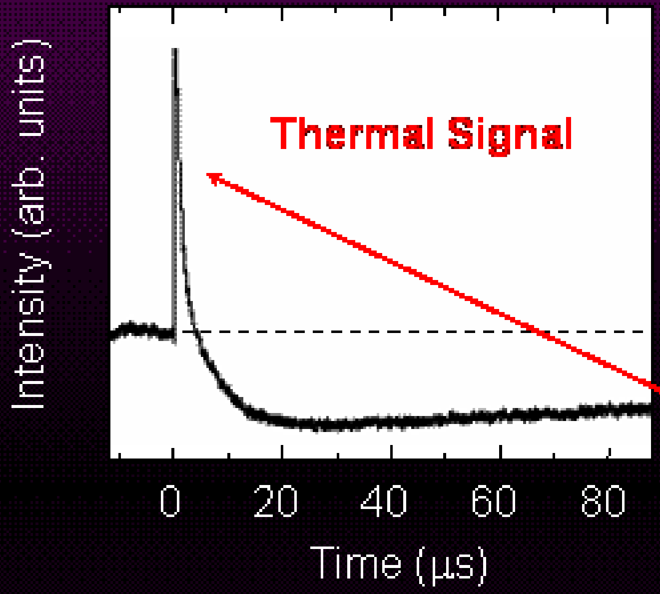
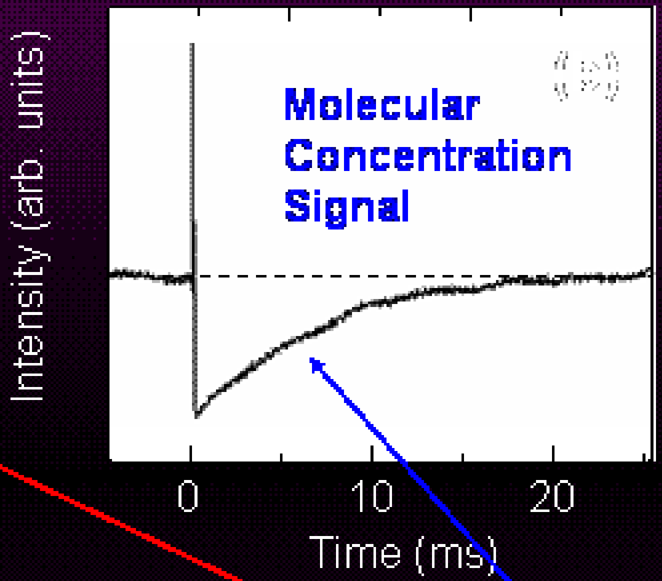


Spiropyran [1', 3', 3'-trimethyl-8-nitrospiro (2H-1-benzopyran-2, 2'-indoline)] in 2-propanol

Time profiles of the TG signals



Thermal Signal



Molecular Concentration Signal

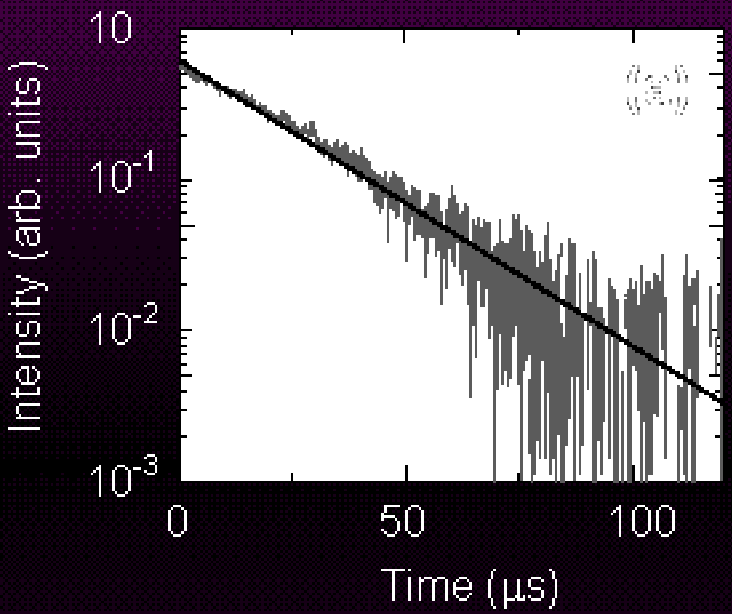
$$I_s(t) \propto \delta n(t)\cos\Delta\phi + \delta k(t)\sin\Delta\phi = a\,\delta T(t) + b\,\delta C(t)$$

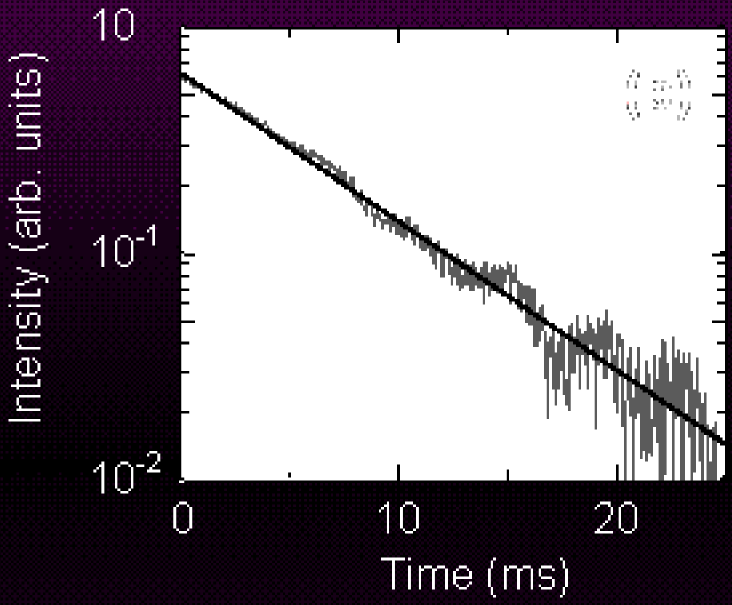
$$\delta n = \left[\left(\frac{\partial n}{\partial \rho}\right)_T \frac{\partial \rho}{\partial T} + \left(\frac{\partial n}{\partial T}\right)_\rho\right]\delta T + \cancel{\left[\left(\frac{\partial n}{\partial \rho}\right)_C \frac{\partial \rho}{\partial T} + \left(\frac{\partial n}{\partial T}\right)_\rho\right]}\delta C$$

$$\delta k = \cancel{\left[\left(\frac{\partial k}{\partial \rho}\right)_T \frac{\partial \rho}{\partial T} + \left(\frac{\partial k}{\partial T}\right)_\rho\right]}\delta T + \left[\left(\frac{\partial k}{\partial \rho}\right)_C \frac{\partial \rho}{\partial T} + \left(\frac{\partial k}{\partial T}\right)_\rho\right]\delta C$$

$C(t)$: Concentration of the excited molecule

Fitting of the TG signals





Thermal Diffusion Coefficient

Experimental value

$D_{th} = 7.1 \pm 0.5 \times 10^{-8}\ m^2s^{-1}$

Calculated value

$D_{th} = 6.8 \times 10^{-8}\ m^2s^{-1}$

Molecular Diffusion Coefficient

Experimental value

$D = 3.0 \pm 0.2 \times 10^{-10}\ m^2s^{-1}$

Calculated value

$D = 2.5 \times 10^{-10}\ m^2s^{-1}$

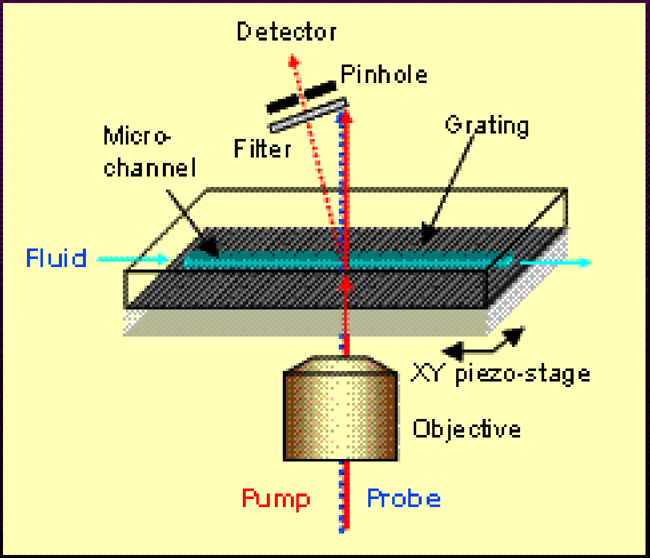
This technique is also powerful tool for molecular dynamics sturdy in solutions.

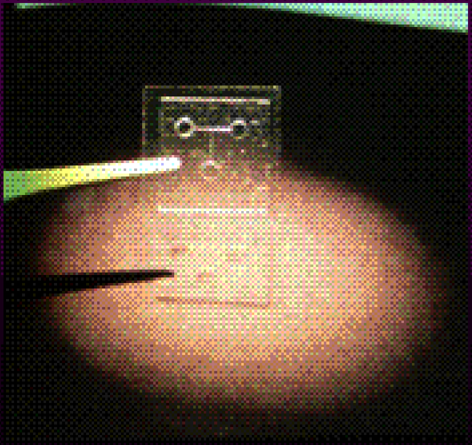
Chemical and Biological Application

Molecular Sensor of Microfluidics

RTV microfluidic devices on the nano-grating substrate

Micro chromatography





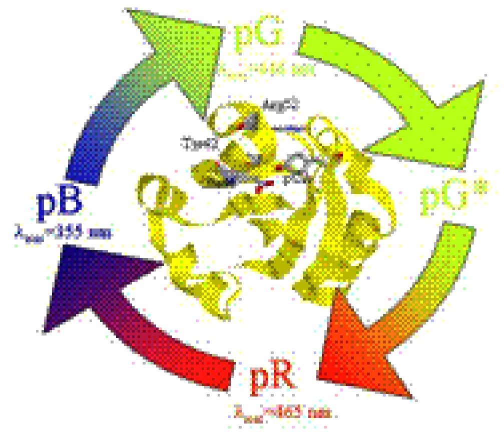
RTV microfluidc device

Monitoring the Dynamics of Biological Proteins

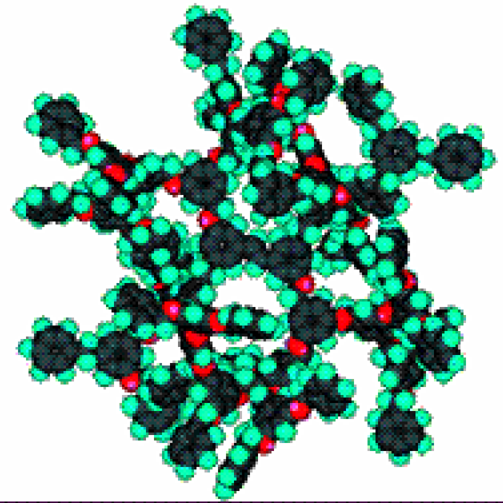
Terazima et al. (Kyoto University) have published for

- Photoactive Yellow Protein
- Rhodopsin
- Myoglobin
- Dendrimers, etc.

By usual TG method



J.Am.Chem.Soc., 122, 8524 (2000)



J.Phys.Chem.A, 107, 6515 (2003)

Summary

- We developed the new technique of the heterodyne detected transient grating measurement by using the fabricated nano and micro gratings. This method is powerful tool for energy and molecular dynamics study in solutions.

- This method has many advantages compared with traditional techniques
    - Simple setting and easy alignment
    - High sensitivity and high S/N ratio (heterodyne detection)
    - High stability (phase shift, beam alignment)
    - Easy analyzing (linear relationship of intensity vs. $\chi^{(3)}$)