Optical Absorption Characterization Using Thermal Waves

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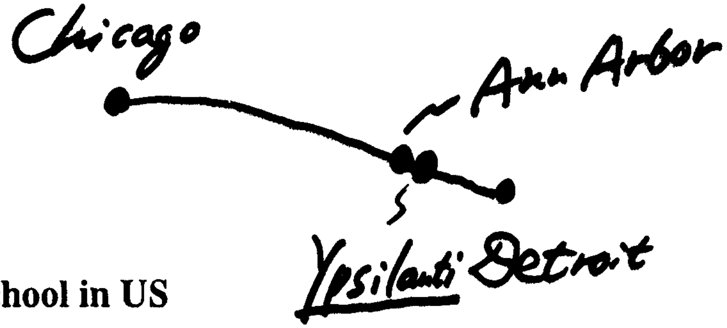
Eastern Michigan University

- **Where?** Ypsilanti, Michigan
  neighbor of University of Michigan
- **When?** Founded in 1849
  as one of the first teacher training school in US
- **What?** #1 producer of school teachers in US
  about 25000 students (80% undergraduates)
- **Responsibility:** Educate future educator



Responsible for future!

New Challenges

Ultra-low level: sub-ppm (e.g. LIGO)

==> **High sensitivity**
~ a few ppb

Contamination: manufacturing
application
characterization

==> **Non-contact**
Noninvasive
In-situ

Nonuniformity: lateral (e.g. defects)
vertical (e.g. interface)

==> **Spatial resolution**

Instability: *In-situ*

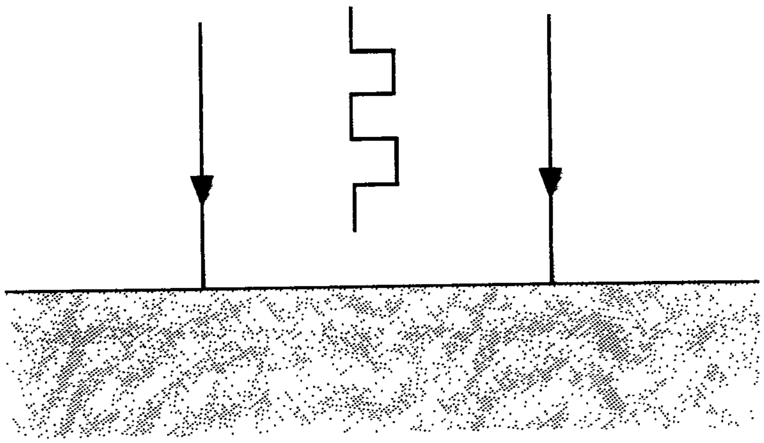
Nonlinearity: Power dependence

Low Cost / Fast / Portable

easy to use

Large Aperture !

What is a Thermal Wave?



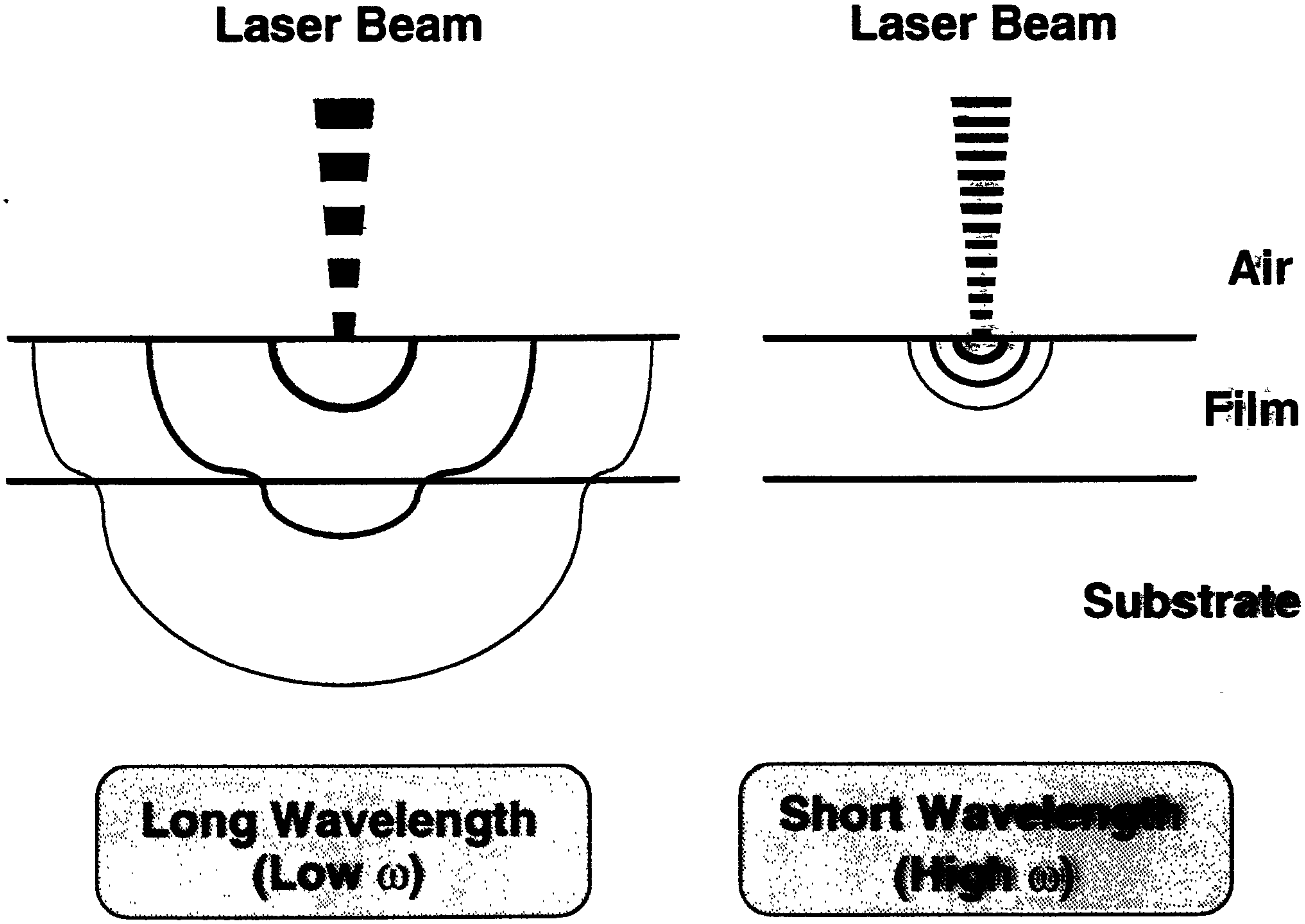
Laser Beam

ω

Air

Sample

$T(r,t)$


Laser Beam
Laser Beam
Air
Film
Substrate
Long Wavelength
(Low ω)
Short Wavelength
(High ω)

Heat diffusion Equation:

$$\boxed{\nabla^2 T = \frac{1}{\alpha} \frac{\Delta T}{\Delta t}}$$

α: thermal diffusivity $\alpha = \frac{\kappa}{\rho c}$

κ: thermal conductivity

ρ: mass density

c: specific heat

Solution in one dimension ----> Plane wave

$$\boxed{T(x,t) = T_o e^{i(qx - \omega t)}}$$

Where the thermal wave number, q, is given by

$$q = (1 + i)(\omega / 2\alpha)^{1/2}$$

Real part ----> Physical temperature rise:

$$\boxed{T(x,t) = T_o\, e^{-x/\mu} \cos\left(\frac{2\pi x}{\lambda} - \omega t\right)}$$

Diffusing length: $\mu = (2\alpha / \omega)^{1/2}$

Wavelength: $\lambda = 2\pi\mu$

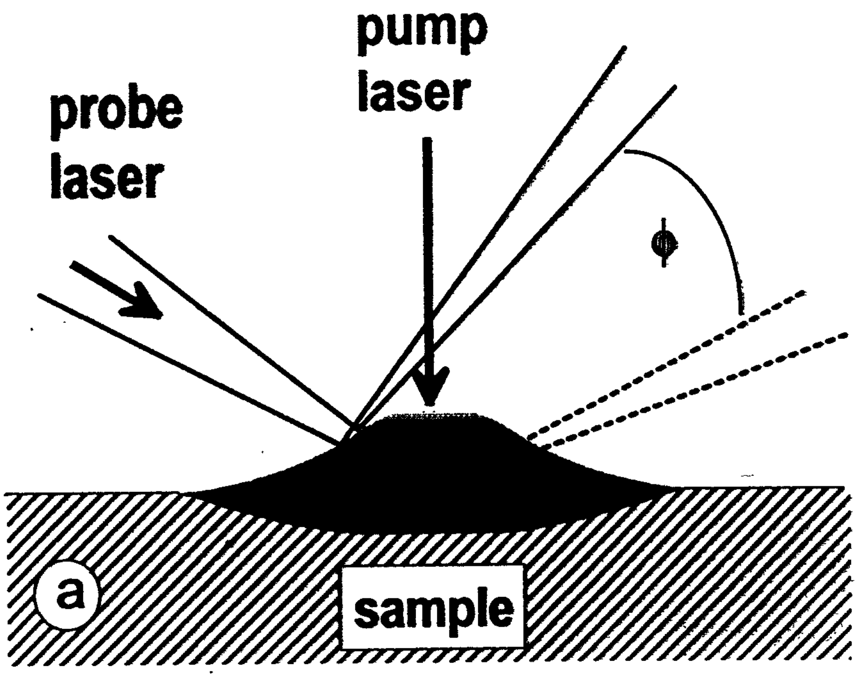
Wave velocity: $v = \frac{\omega\lambda}{2\pi} = (2\alpha\omega)^{1/2}$

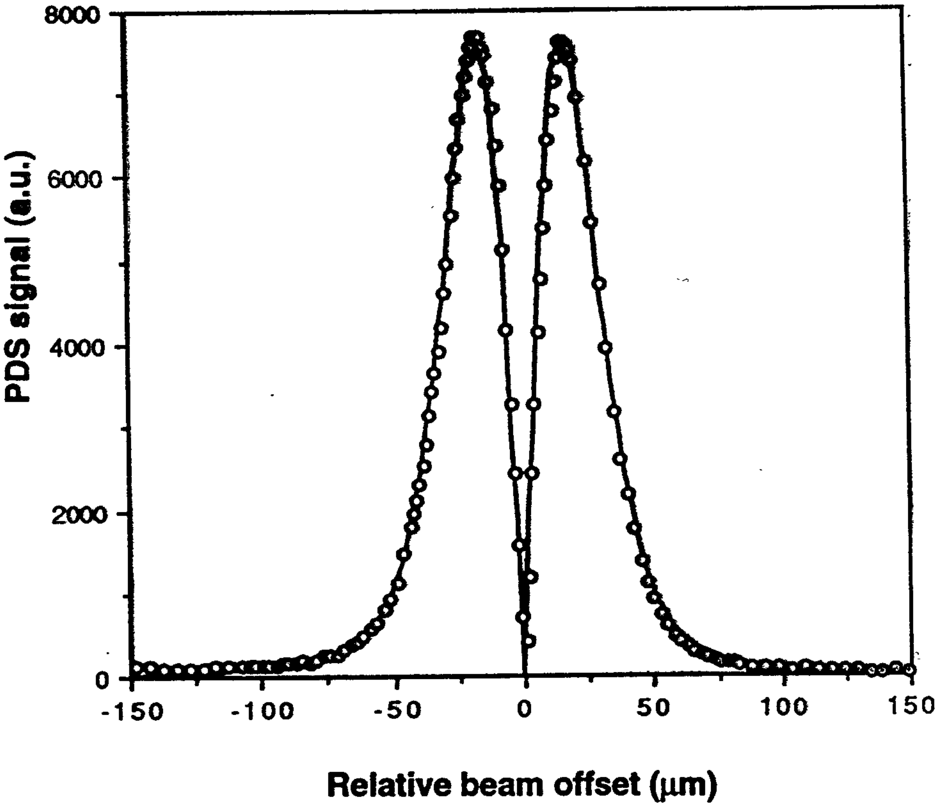
Heavily damped

Very dispersive

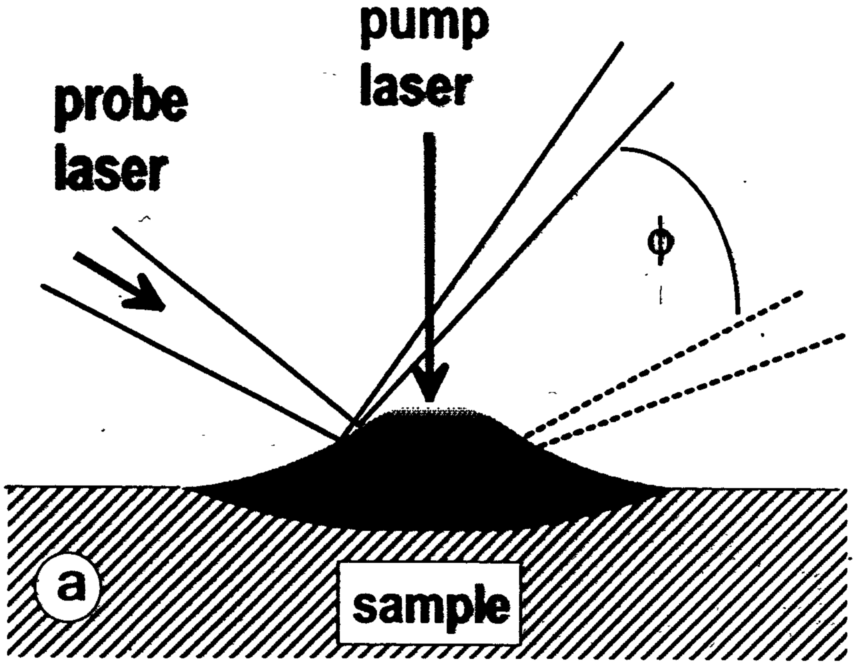
Earliest reference: Ångstrom, Ann. Physik, 114 (1861)

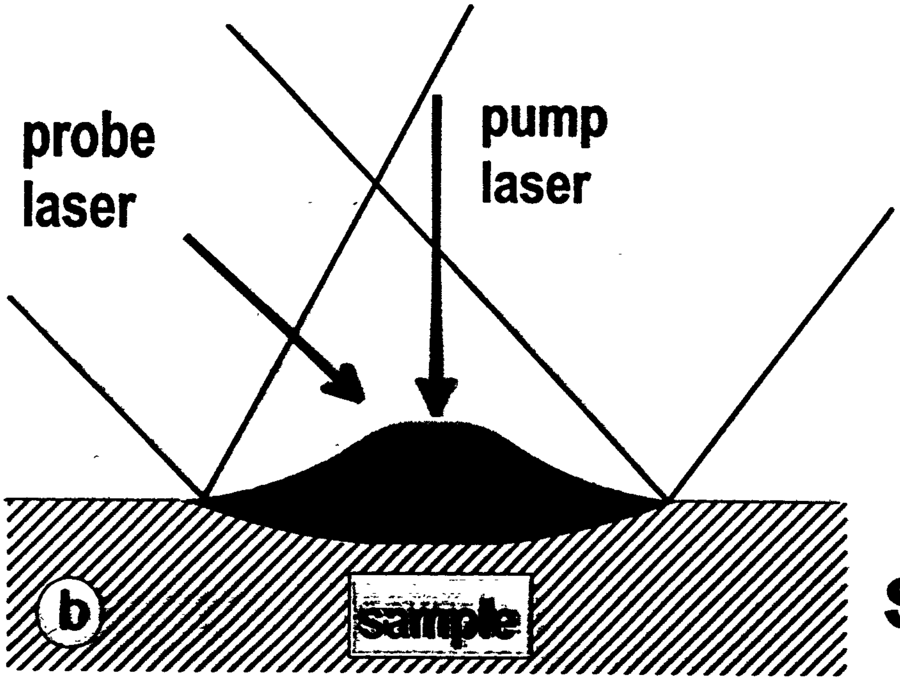
Detection of photothermal deformation using photothermal deflection spectroscopy (PDS)





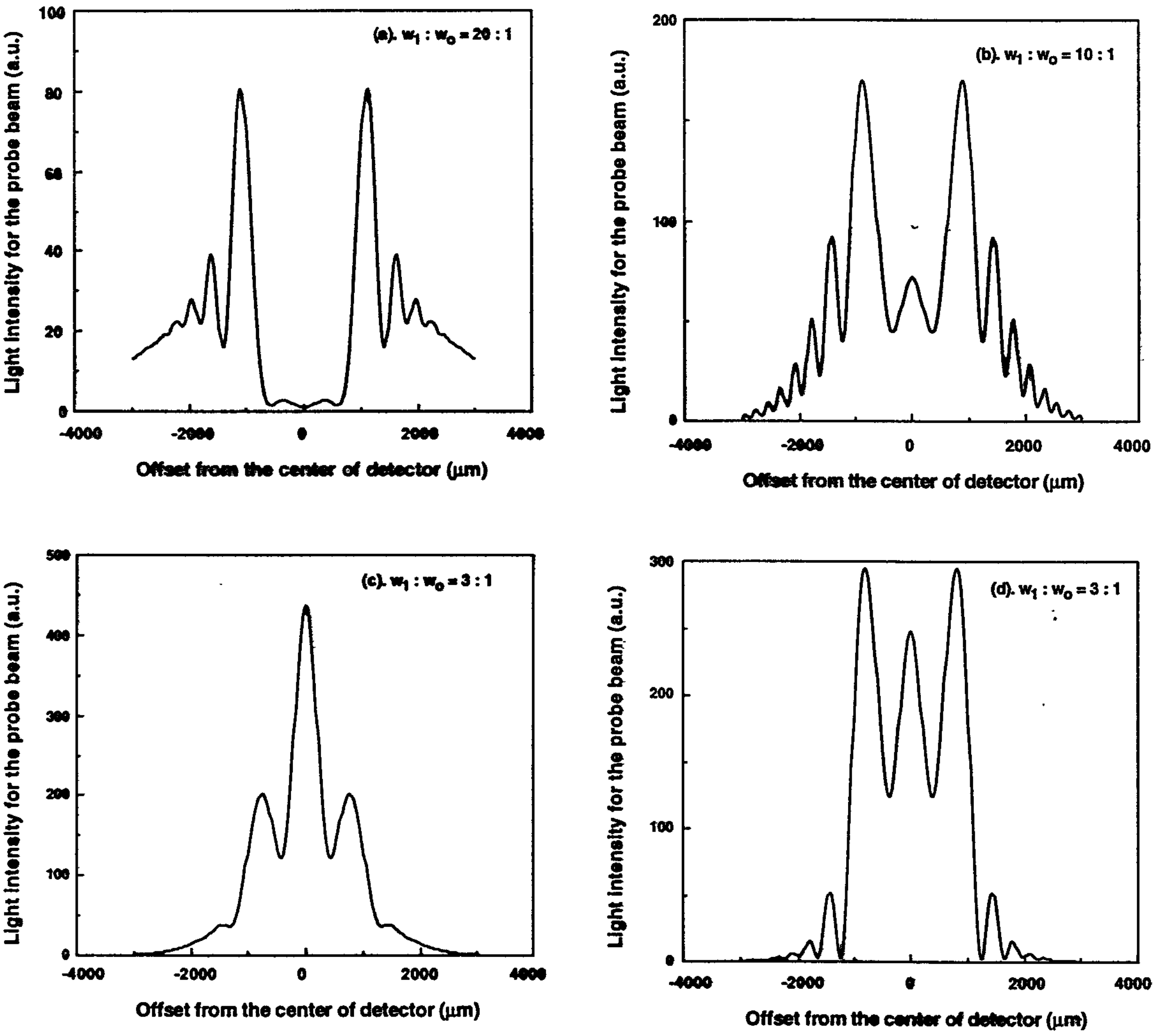
Comparison between PDS and Surface Thermal Lensing (STL)



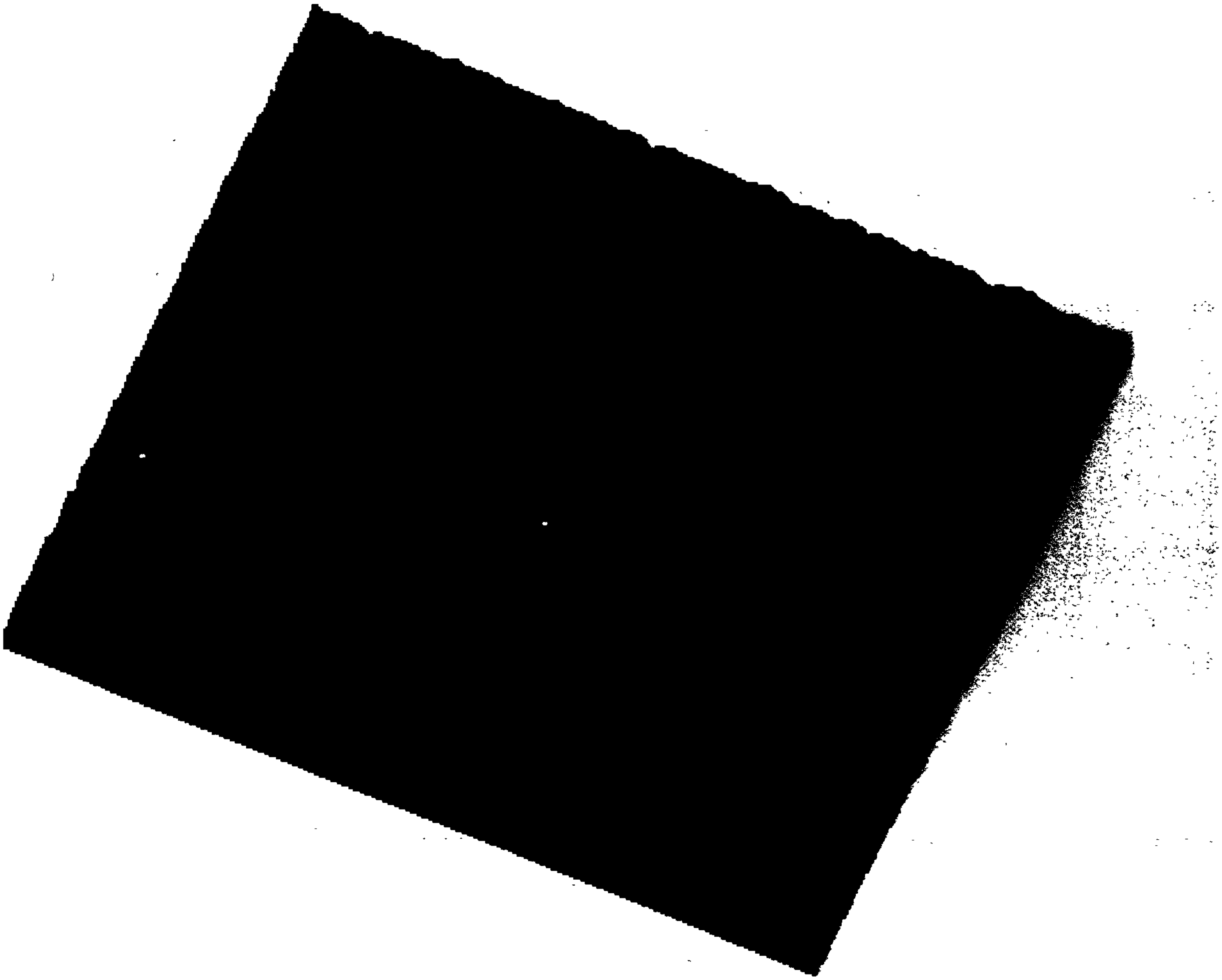


STL

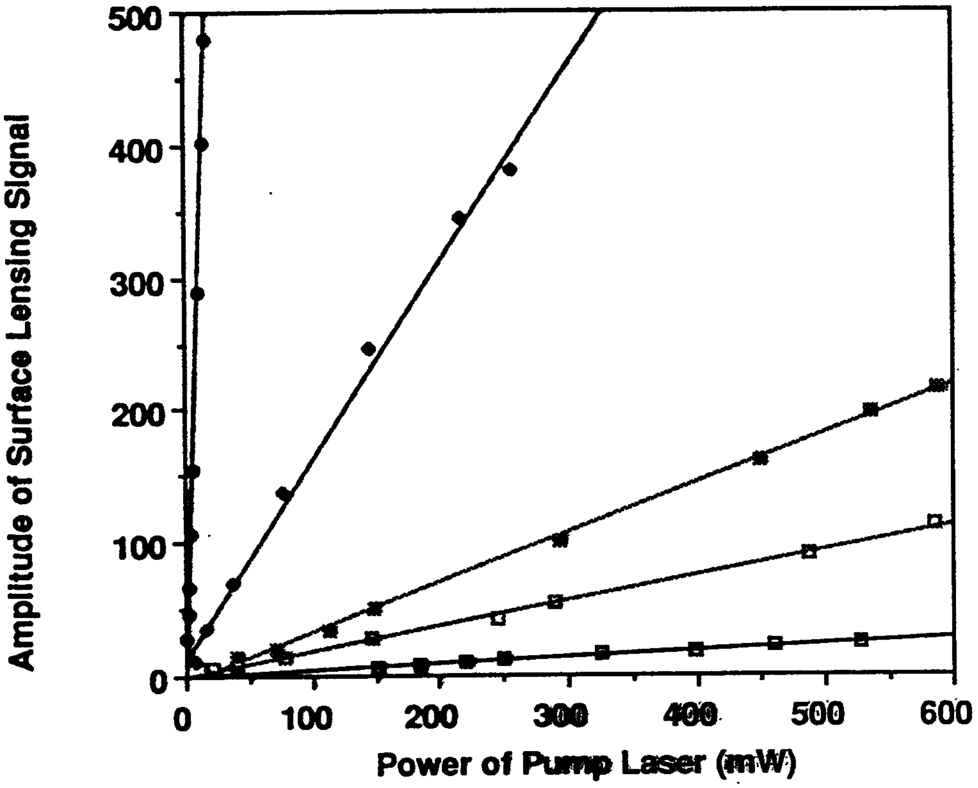
Modeled Results of the Diffraction Pattern of the Probe Laser Beam in the Detection Plane



Probe beam profile in the observation plane



Absorption Measurement Results Using Surface Lensing Effect

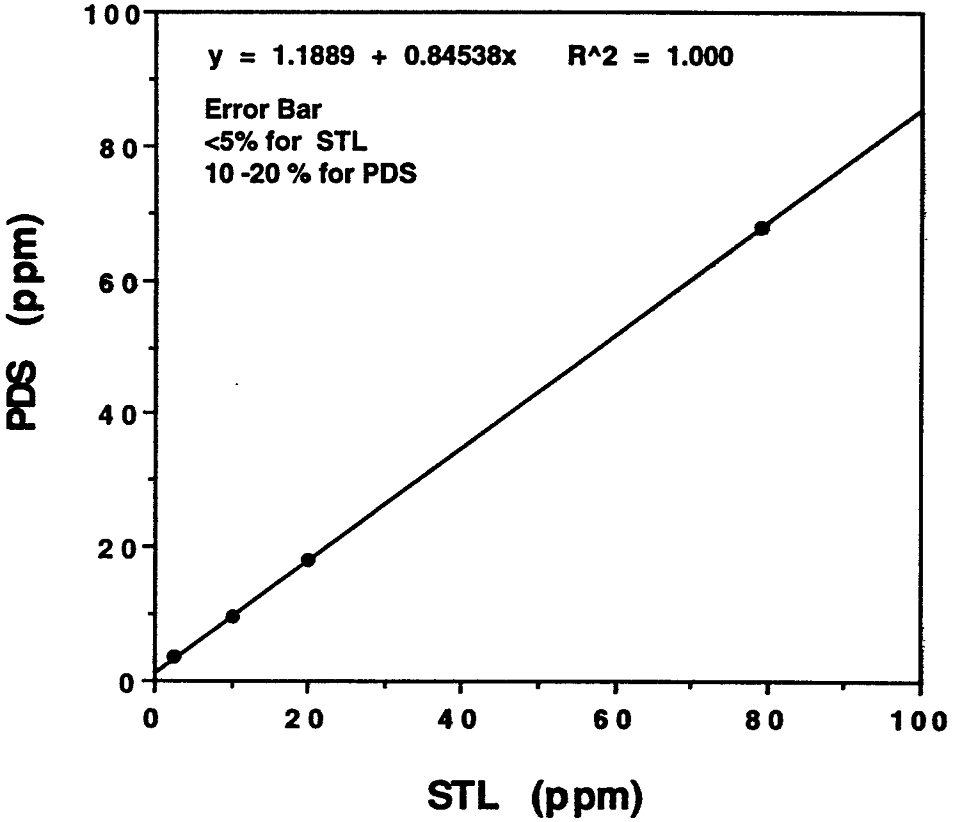


Sample	Fitting result	Absorption
● Ag film on BK7	y = 1.3005 + 28.401x R^2 = 0.999	1.52×10^{-2}
◆ TiO2 on BK7	y = 11.582 + 1.4880x R^2 = 0.995	7.86×10^{-4}
▪ Ta2O5 on BK7	y = - 4.4776 + 0.37251x R^2 = 0.999	1.99×10^{-4}
□ ZrO2 on BK7	y = 0.69165 + 0.18633x R^2 = 0.998	9.97×10^{-5}
■ SiO2 on BK7	y = - 0.76352 + 4.9054e-2x R^2 = 1.000	2.63×10^{-5}

Absorption measured by using STL and their comparison with those by our in-house PDS

Sample	SiO2	ZrO2	Ta2O5	TiO2	Accuracy
STL	2.6 ppm	10 ppm	20 ppm	79 ppm	< 5.0 %
PDS	3.5 ppm	9.6 ppm	18 ppm	68 ppm	~ 10 - 20%

Correlations: STL vs PDS



4.2 *In-situ* studies of optical absorption

Many thin films are not stable under laser irradiation [9,10, 23, 24]. Even for stable optical components, its performance may still be a function of time due to possible contamination process. STL, thanks to its time resolution (typically a few ms), presents itself as a powerful tool for monitoring in real time the dynamics of the change, as shown by the example in Figure 7. In this example, the sample is under Ar$^+$ laser irradiation when the absorption data is taken. In about ten minutes, the absorption of the sample was reduced by a factor of about seven.

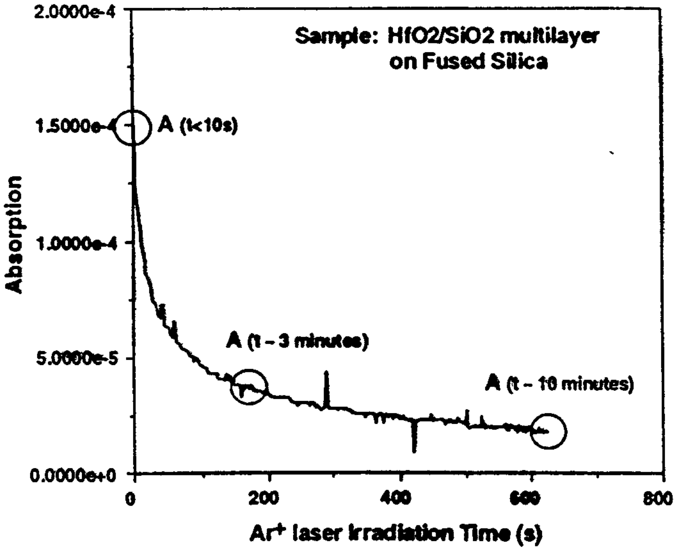
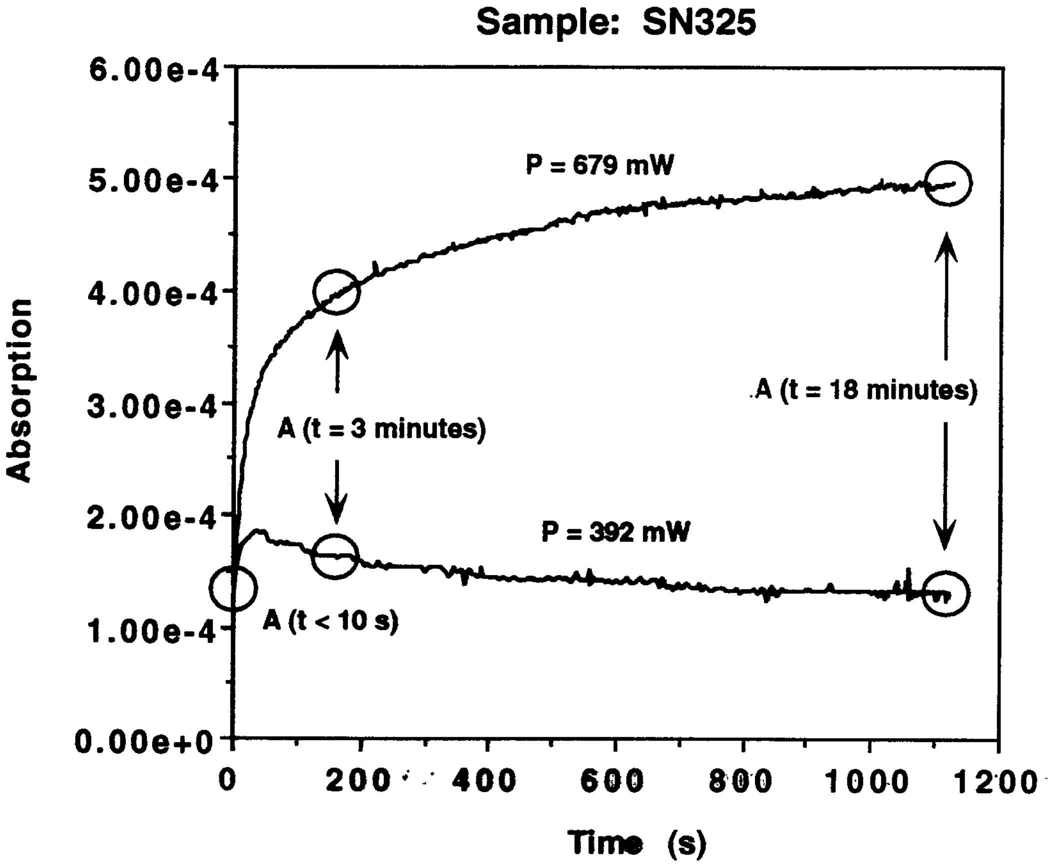
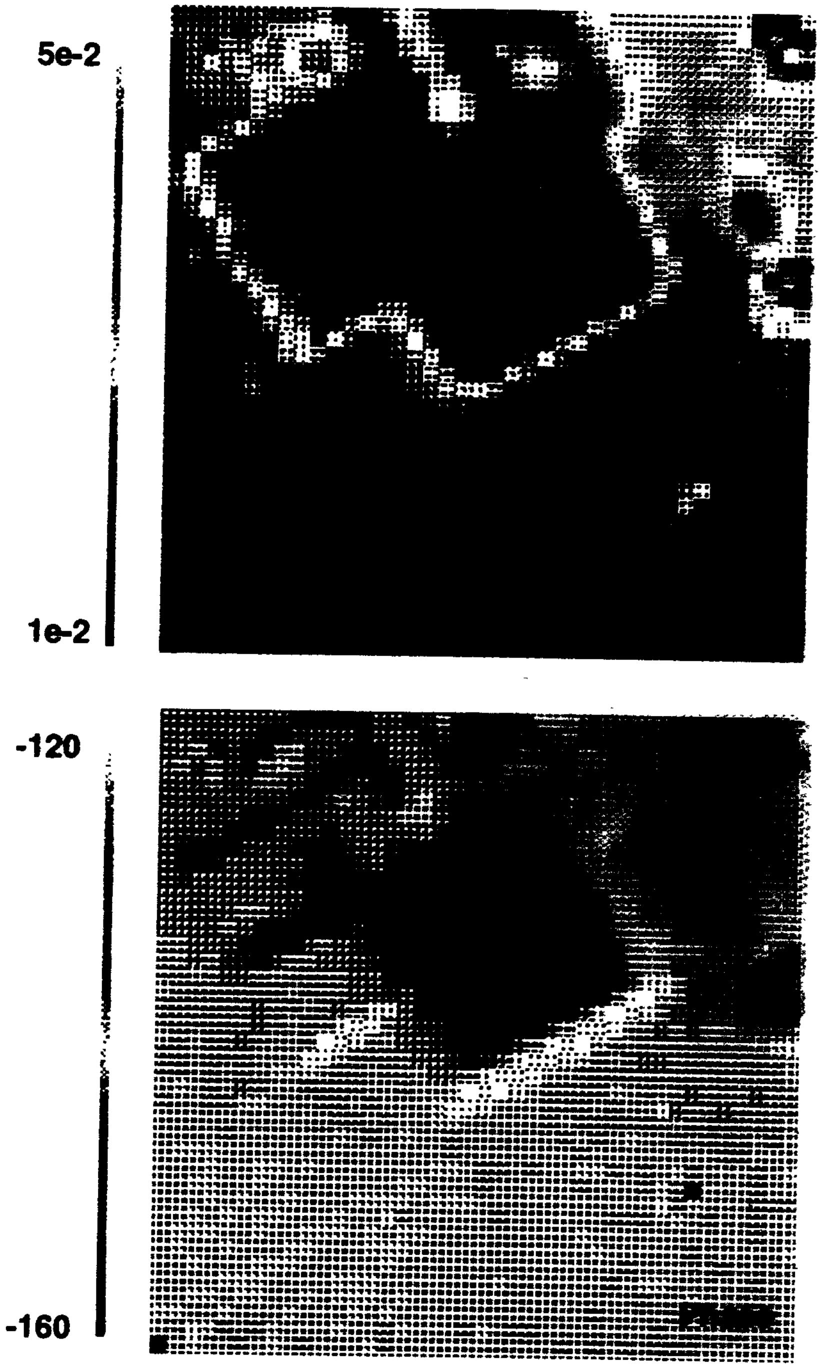


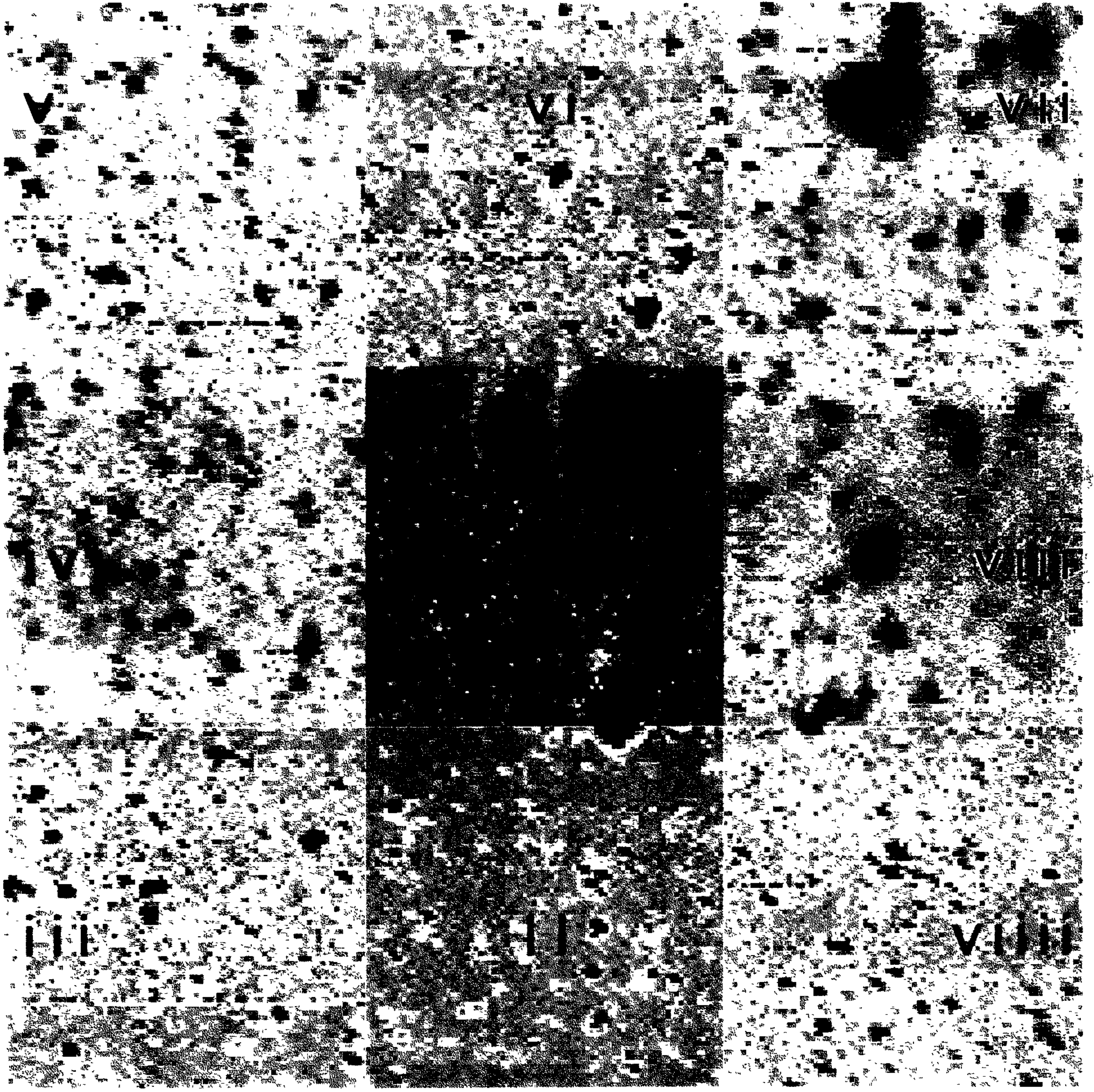
Figure 7. Laser-induced reduction in optical absorption observed in real time using the STL method.



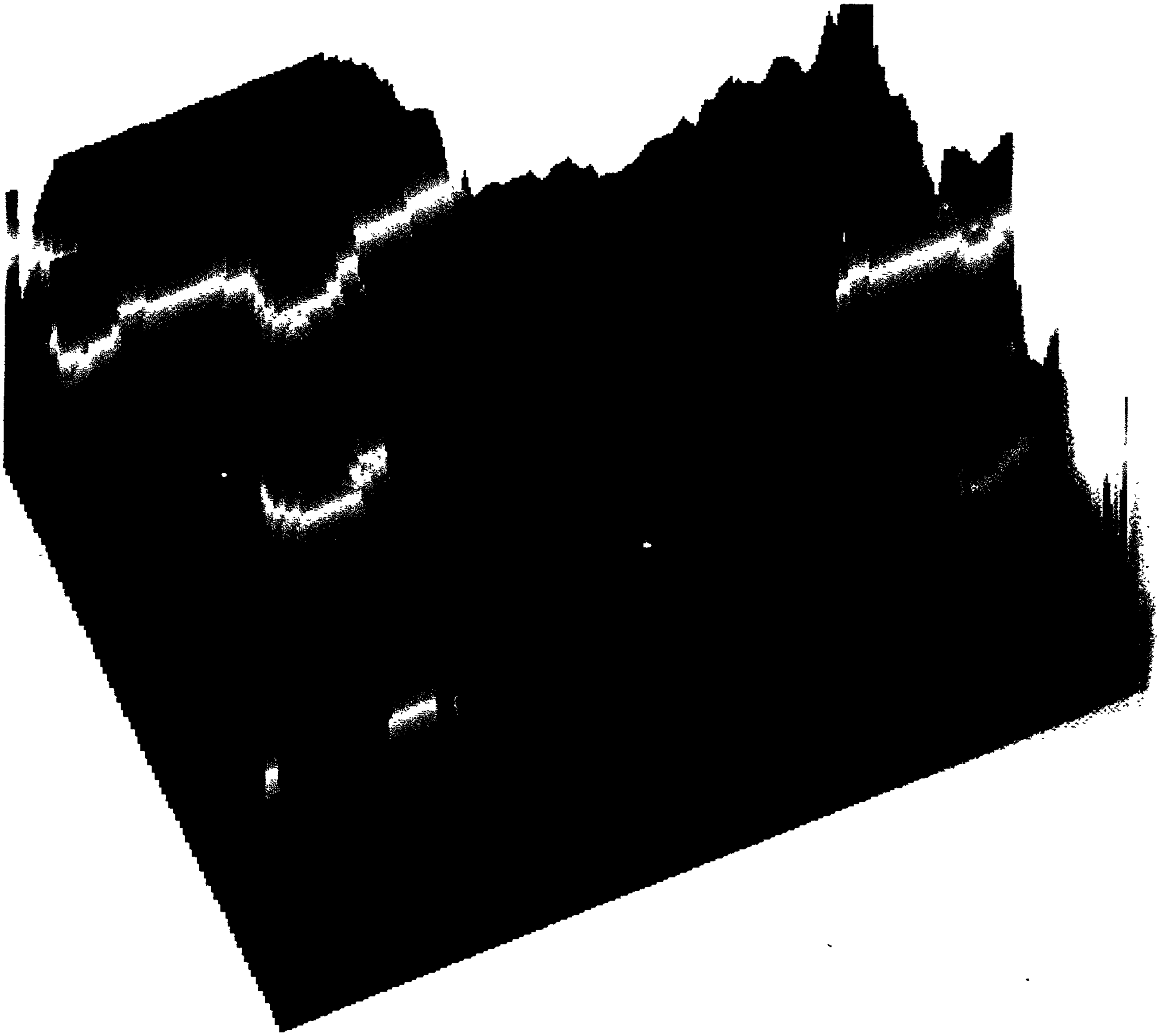
Sample: SN325
6.00e-4
5.00e-4
4.00e-4
3.00e-4
2.00e-4
1.00e-4
0.00e+0
Absorption
0
200
400
600
800
1000
1200
Time (s)
P = 679 mW
P = 392 mW
A (t = 3 minutes)
A (t = 18 minutes)
A (t < 10 s)



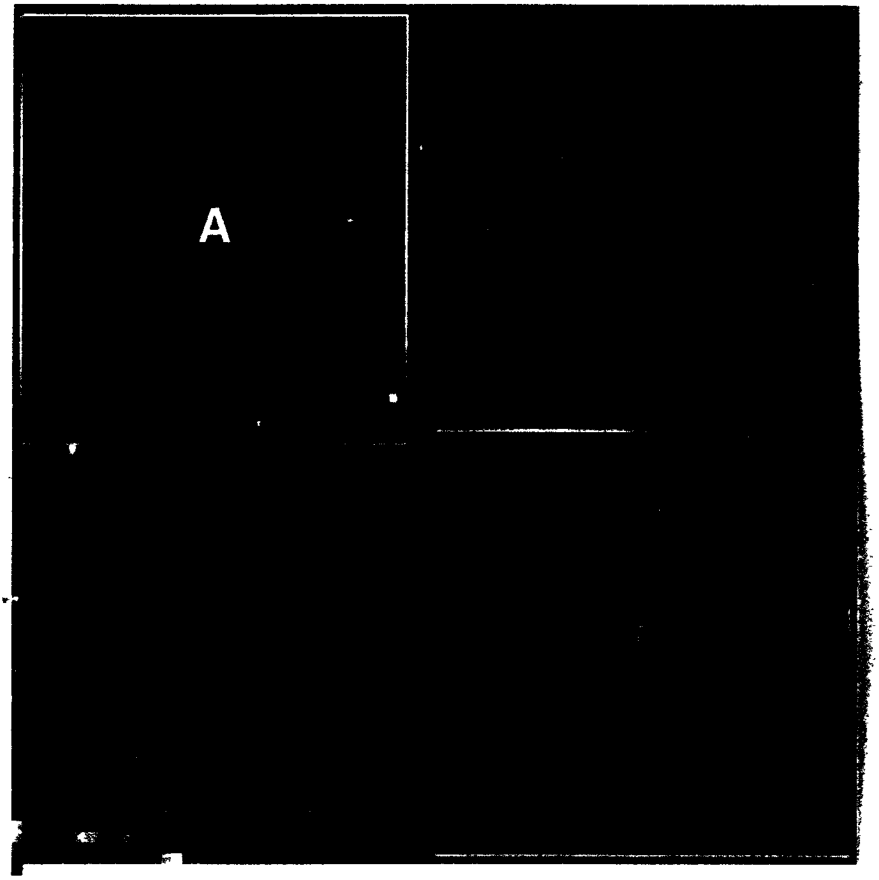
Scanned area: 600 μm x 600 μm
Modulation frequency: f = 500 Hz



Sample: SNB282
Scanned area: 3 mm x 3 mm
Spatial resolution: ~10μm



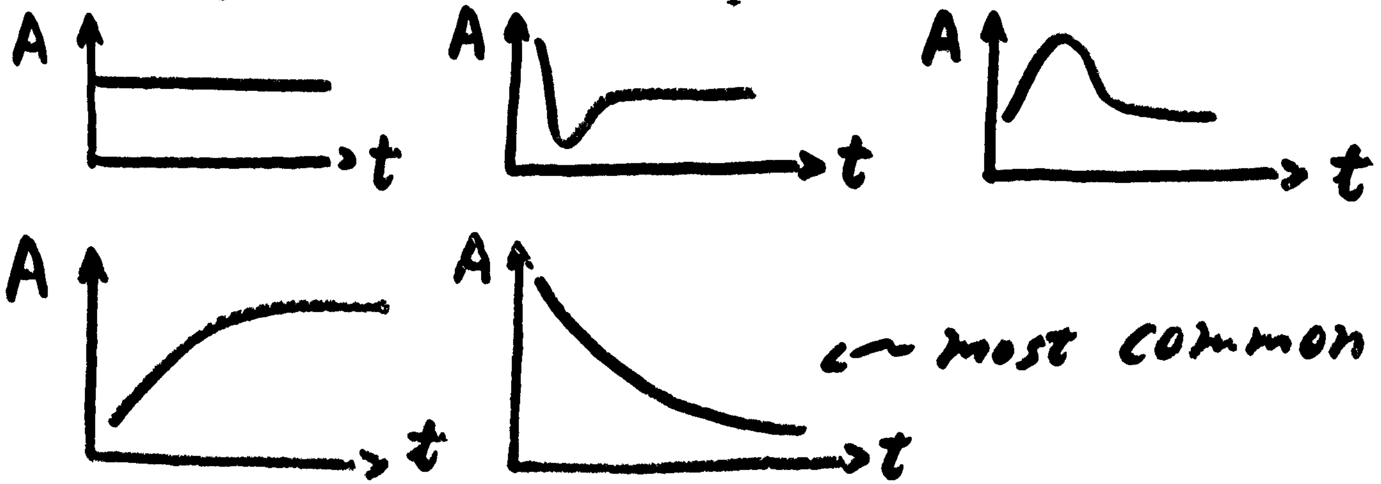
Sample 325



<u>Sampling Area</u>	<u>Averaged Pixel Value</u>			
Whole picture	Mean:	16.67	Dev:	20.20
Area A	Mean:	12.41	Dev:	6.86
Area B	Mean:	24.18	Dev:	34.50

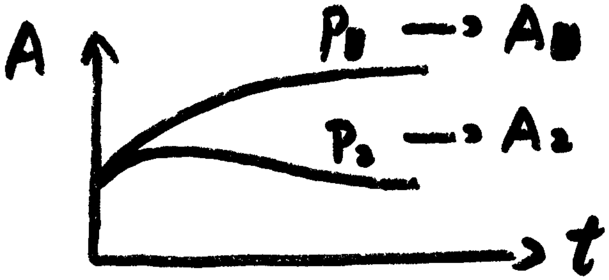
Observation Summary

1. Absorptance has a time-dependent behavior



← most common

2. Absorptance has a non-linear behavior



$P_1 \simeq 1.5\, P_2$

$\Rightarrow A_1 \simeq \underline{4.5}\, A_2$

3. Coatings are spatially non-uniform in absorptance.

Conclusions

Surface Thermal Lensing (STL)

Sensitive: 10 ppb at 1 watt incident power

Stable: precision < 5% at 0.5 ppm absorptance

Fast: time resolution ≈ 10 msec

Spatial resolution: ≈ 1 μm

Non-contact and non-destructive

Low cost absorptance system

Small footprint (< 2 ft^2)

Easy to use

Recommended procedure for absorptance measurements for high power laser applications

Required:

1. Measurement conditions are as close as possible to operational conditions (e.g. power density).

2. Record time-dependence (on the order of a few minutes).

Optional:

3. Random sampling or 2-dimensional scanning to assess spatial non-uniformities.

Academics

4. Non-linear mechanisms

5. Absorptance sources and distributions

system will combine the advantage of being both highly sensitive and easy-to-use, as in the case for the STL technique.

Fig. 5 shows the design of the experimental setup. The CPD system is going to share with the STL method the same pump laser source, and the two systems are designed such that they can work both independently and simultaneously.

For absorption measurements of bulk materials using CPD, the calibration of the absorption value is going to be achieved by using accurate modeling. The model will be verified by samples with known absorption before it is used for calibration.

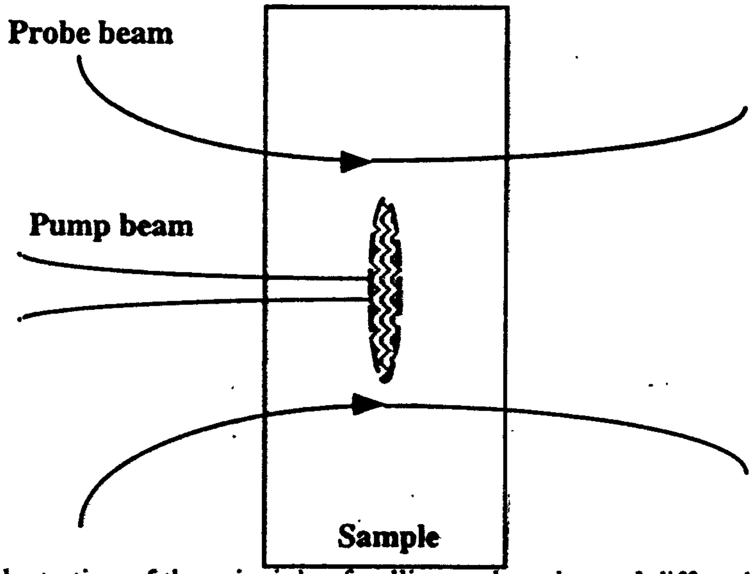


Figure 4. Illustration of the principle of collinear photothermal diffraction (CPD).

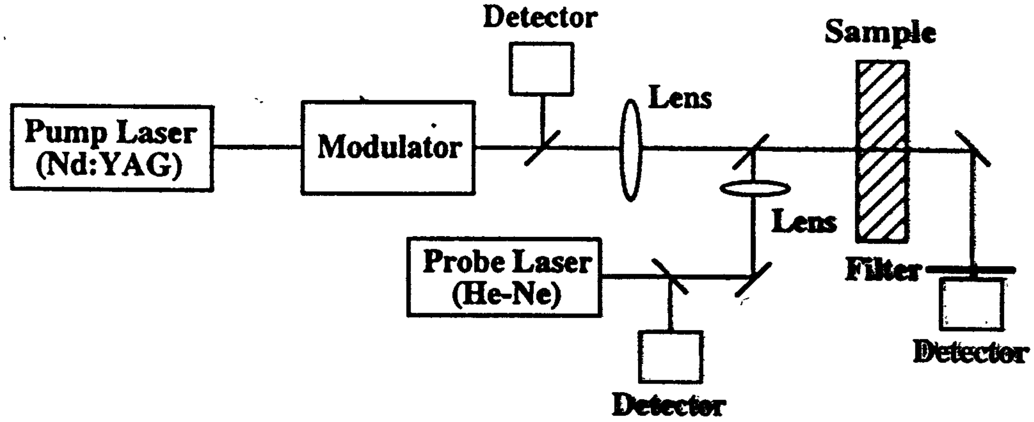


Figure 5. Depiction of the experimental setup for CPD.

4. Study of Absorption Mechanisms for Thin Film Coatings

For dielectric thin films the absorption loss is usually higher than that of the corresponding bulk material and depends strongly on the specific film deposition processes. To reduce the absorption and, hence, to develop high quality optical coatings, it is necessary to better understand the absorption mechanisms. For this reason we propose to use the third year of the project to perform the following studies.

For STL, in contrast to PDS, a probe beam with a size similar to or larger than the lateral dimension of the thermally deformed area is reflected from the sample surface, as shown in Figure 1 (b). In this case the deformed area on the sample surface is acting as a curved mirror which distorts the wavefront of the probe beam. The shape of the surface deformation is thus recorded in the diffraction pattern of the reflected probe beam, which can be analyzed by using either a CCD camera or a scanned photo-detector.

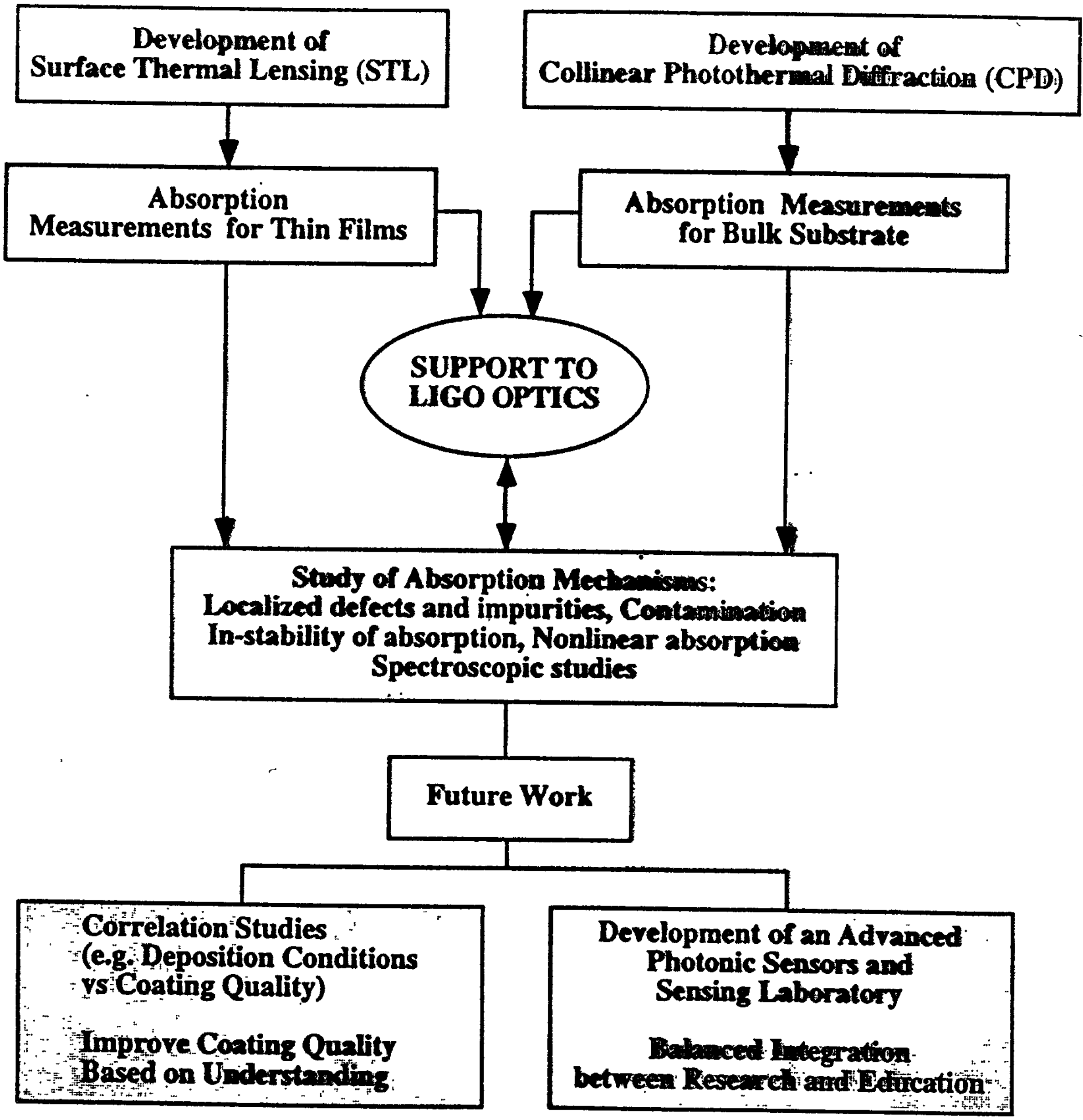


Figure 1. Outline of the proposed work.

The advantages of STL over PDS and other photothermal techniques are multiple. It has the same high sensitivity but it avoids the critical alignment requirements for PDS, and, hence, is an easy-to-handle method which can be easily applied to the study of a variety of materials in different environments. Furthermore, if a CCD camera is used for detecting the diffraction pattern, STL obtains the full field information of the surface deformation.