

Article ID 1004-924X(2005)04-0430-05

# Weak absorption test and defect analysis of optical coatings

HE Hong-bo, LI Xia, FAN Shu-hai, ZHAO Yuan-an, SHAO Jian-da, FAN Zheng-xiu

(Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China)

**Abstract :** Surface thermal lensing technique was developed into a high-sensitive apparatus for weak absorption test and defect analysis of optical coatings. A continuous-wave 1 064 nm Nd:YAG laser and a He-Ne laser were employed as pump source and probe source, respectively. Low noise photoelectrical components and a lock-in amplifier were used for photo-thermal deformation signal detection. In order to improve sensitivity, the apparatus configuration was optimized by choosing appropriate parameters, including pump beam spot size, chopper frequency, detection distance, waist radius and position of probe beam. Coating samples were mounted on a  $x-y$  stage. Different procedures, such as single spot, linear scan and 2-dimension area scan, could be performed manually or automatically. Various optical coatings were prepared by both electron beam evaporation and ion beam sputtering deposition. High sensitivity was obtained and low to  $1 \times 10^{-7}$  weak absorption was tested in low-loss coating samples. For the sensitivity extreme of the system,  $1 \times 10^{-8}$  absorption was reason out to be measured by surface thermal lensing technique. Very small standard deviation was achieved for the reproducibility evaluation. Moreover, a spatial resolution of 25 micron was proved according to the area scan which traced out the profile of photo-thermal defects inside optical coatings. The system was employed in the analyses of optical absorption, absorption uniformity and defect characterization, and revealed the relationship between laser-induced damage and absorption of optical coatings.

**Key words :** surface thermal lens; absorption; coating defect; optical coating; sensitivity

## 1 Introduction

In modern optics, especially laser technology, absorption is one of the most important characters which must be considered, not only for optical properties, but also for laser-induced damage threshold (LIDT). For example, absorption defect has played a great role influencing laser induced damage behaviors of the dielectric optical coatings. In many applications, very weak absorption,  $1 \times 10^{-6}$  or less, should be measured and controlled.

However, the sensitivity of the best regular spectrometer is only low to 0.1%. Solutions had been found to resolve the weak absorption prob-

lem. The most useful techniques are laser calorimetric technique<sup>[1]</sup>, mirage effect<sup>[2]</sup>, photothermal deflection<sup>[3]</sup>, and surface thermal lensing (STL)<sup>[4-5]</sup>. They have a very high sensitivity of  $1 \times 10^{-6}$ ,  $1 \times 10^{-7}$ , or less.

In Shanghai Institute of Optics and Mechanics (SIOM), photothermal methods for weak absorption measurement were studied for many years, especially for STL. The SIOM research group had been included in the "Round Robin" weak absorption measurement from January 1998 to November 1999. Fig. 1 gives some results collected from the attendees of different countries. STL. 3 stands for the SIOM results which are close to the overall average.

Efforts have been made in the recent years

**Received date :**2005-06-06; **Revised date :**2005-06-16.

**Foundation item :**Project (No. 011661076) funded by science and technology community shanghai municipal.

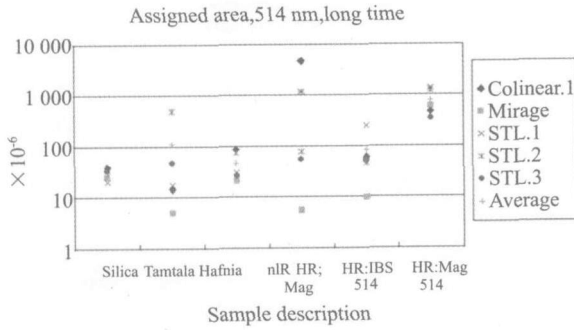


Fig. 1 Results of " Round Robin " weak absorption measurement

to develop the experimental setup into a practicable apparatus in SIOM.

## 2 Simplified principles

According to thermal transmission equation and linear expansion theory, under the irradiation of modulated laser beam, the photothermal deformation of an ideal optical coating, as shown in Fig. 2, was deduced and simplified theoretic relationship was given as

$$u = C_1 A P_{pump} , \tag{1}$$

Where,  $u$  stands for the average central height of the alternative rise caused by the modulated Gaussian pump beam.  $A$ ,  $P_{pump}$  and  $C_1$  represent absorption of optical coating, power of pump beam and a constant related to substrate and pump beam, respectively.

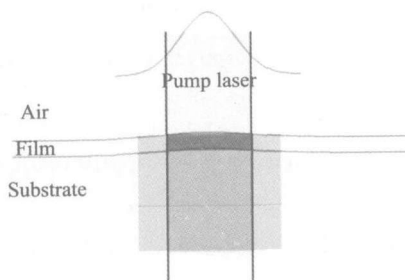


Fig. 2 Photothermal deformation of optical coating

Fig. 3 gives the schematic drawing of surface thermal lens effect. Based on Fresnel diffraction theory, thermal lens amplitude, namely,

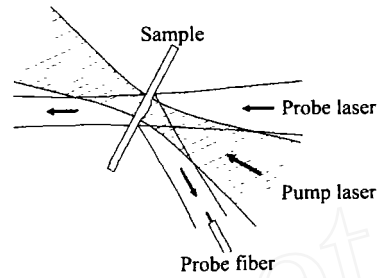


Fig. 3 Schematic drawing of surface thermal lens effect photothermal signal  $S$  shows the alternative intensity of the reflected pump beam center, could be given as

$$S = C_2 u P_{probe} , \tag{2}$$

Where,  $P_{probe}$  and  $C_2$  are power of probe beam and a constant related to fiber position and probe beam, respectively.

Therefore, photothermal signal  $S$  is proportion to absorption  $A$  according to the above equations and satisfies a linear relationship with  $A$  as the following equation

$$S = CA P_{pump} P_{probe} , \tag{3}$$

Where,  $C$  is a system constant.

Absorption of calibration samples are easy to be tested by Perkin-Elmer Lambda-900 spectrometer, and after calibration, absorption of different kinds of optical coatings could be conveniently measured according to equation(3).

## 3 Configuration optimization

A CW 1 064 nm laser was adopted as pump laser in the system, with a variable power from 20 ~ 90 W. A 30 mW He-Ne laser was employed as the probe laser. In order to get higher photothermal signal  $S$  and higher sensitivity of weak absorption coating samples, the system configuration had been optimized by choosing appropriate parameters, including pump beam spot size, chopper frequency, detection distance, waist radius and position of probe beam. According to our experimental and calculation, the main adjustments to the system configuration are briefly

explained as followings.

- Smaller pump beam on coating surface is helpful for improving both sensitivity and spacial resolution.

- Smaller probe beam waist radius is good for higher sensitivity because of the increasing signal to noise ratio. Making the system more compact is another profit.

- A proper probe beam waist position can give higher thermal lens amplitude.

- A proper detection position is also important for thermal lens amplitude.

- Lower chopper frequency provides longer thermal diffusion length and higher photothermal signal.

### 4 Performance

Linearity is the most important thing for the accuracy of the apparatus. Fig. 4(a) ,(b) and (c) show that the STL signal (photothermal signal) is proportion to the pump laser power from 6 mV to several  $\mu\text{V}$ . That means there is a very good linearity for the measurement of absorption of optical coatings.

Many optical coating samples were measured for absorption using the apparatus. As shown in Fig. 5, low to  $5.5 \times 10^{-6}$  (even  $2 \times 10^{-6}$ ) could be tested directly. Since the STL signal is relatively high enough for the lock-in amplifier, it seems the sensitivity should be much better than  $1 \times 10^{-6}$  level. Actually, it is

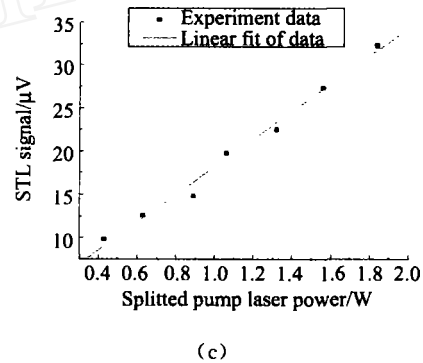
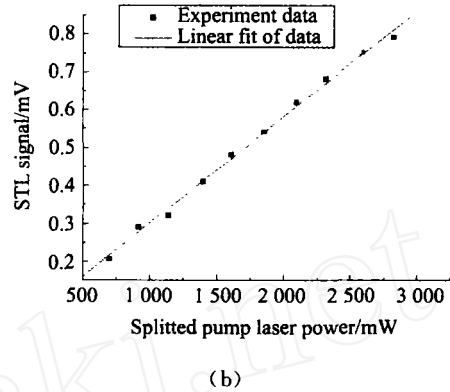
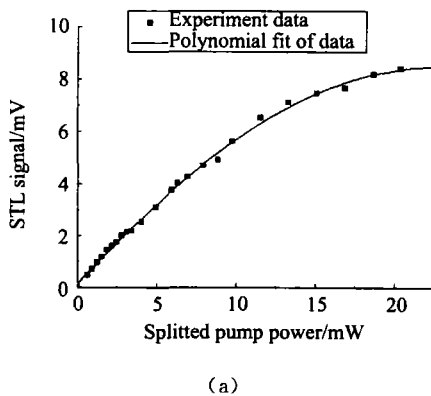


Fig. 4 Photothermal signal vs. pump laser power for samples of different absorption values.

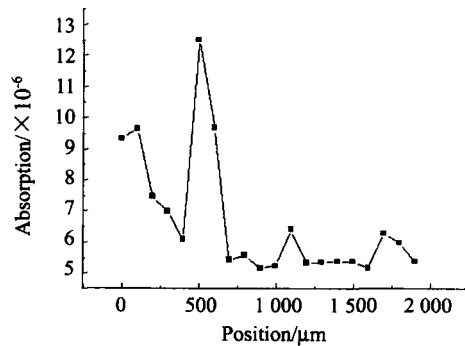


Fig. 5 Measured absorption results of a weak-absorption coating sample

not difficult to deduce the sensitivity of the apparatus as followings.

According to equation (3) , for absorption of  $5.5 \times 10^{-6}$  ,

$$9.7 \mu\text{V} = C \times 5.5 \times 10^{-6} \times 20 \text{ W}$$

Suppose the noise level is  $0.2 \mu\text{V}$  ,

$$0.2 \mu\text{V} = C \times A_{\text{min}} \times 20 \text{ W}$$

Therefore , sensitivity can be deduced as

$$A_{\text{min}} = 1 \times 10^{-7}$$

A very good sensitivity of  $1 \times 10^{-7}$  was achieved and approved in our experimental.

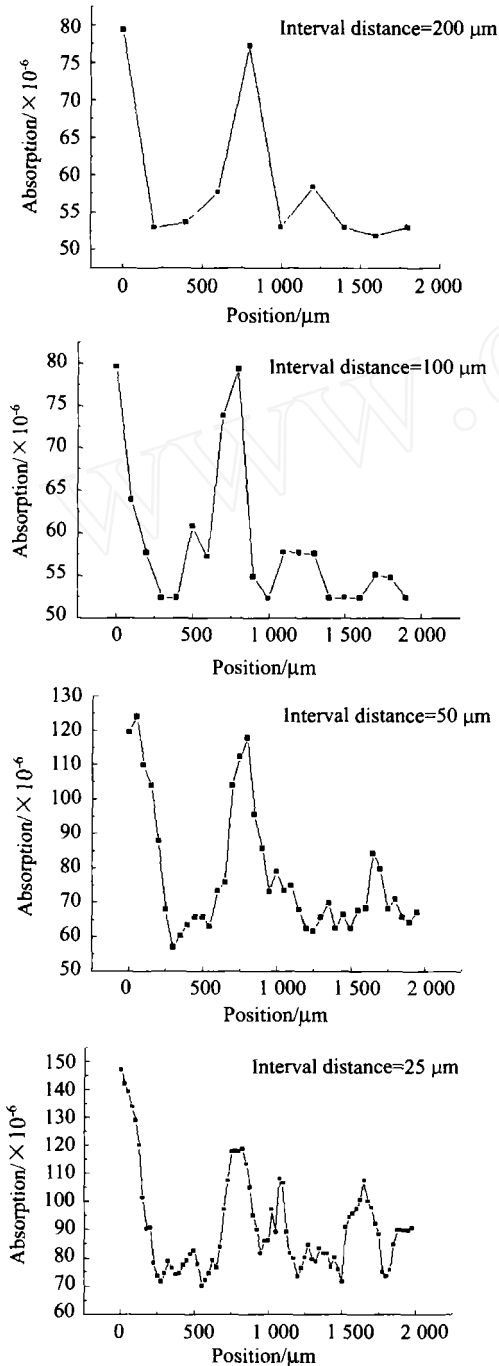


Fig. 6 Absorption linear scanning of different interval distances on the same sample

In fact, actual noise could be low to 100 nV, even 10 nV, and the integral time of lock-in amplifier could be extended from 3 s to 10 s even 30 s, the utmost sensitivity was estimated to be

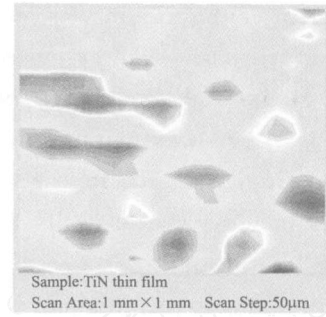


Fig. 7 An example of absorption scanning test

around  $1 \times 10^{-8}$ .

Repeatability of absorption measurement is also very important. The linear scanning data of absorption in Fig. 6 were tested with different interval distances on the same coating sample. From 200 μm to 25 μm, more details were displayed but the profiles exhibited many similarities.

Absorption measurements were performed not only for linear scanning, but also for 2-D scanning. It could give very important information of the defect distribution, defect size and absorption value of defects or contaminations, as shown in Fig. 7. Moreover, a 25 μm spacial resolution was obtained for the photothermal defect microscopy.

## 5 Applications

The recent progresses in weak absorption measurement are very useful for various kinds of analyses on absorption of optical coatings, such as single spot, linear scan and 2-D raster scan of weak absorption, as well as time dependence of absorption. On the other hand, the technology can be used in different applications including absorption uniformity, LIDT, defect distribution, photo-thermal microscopy.

## 6 Conclusions

Surface thermal lensing was developed into a practicable apparatus in SIOM, CAS.

The system configuration was optimized to get better performance, such as perfect linearity, high sensitivity and good repeatability.  $1 \times 10^{-6}$  level absorption was measured directly, a very good sensitivity of  $1 \times 10^{-7}$  was achieved and approved in our experimental. The utmost sensitivity was estimated to be  $1 \times 10^{-8}$ .

The achievements in thermal lensing are

helpful and important for optical coating characterization.

## 7 Acknowledgement

The research was supported by a project (011661076) funded by Science and Technology Community Shanghai Municipal.

### References :

- [1] ISO standard:11551, 1997, revised 2003, Optics and optical instruments-lasers and laser-related equipment-test method for absorptance of optical laser components[S].
- [2] J. C. Murphy, L. C. Aamodt. Photothermal spectroscopy using optical beam probing: Mirage effect[J]. *J. Appl. Phys.*, 1980, 51(9):4580-4588.
- [3] W. B. Jackson, N. M. Amer, A. C. Boccara, D. Fournier. Photothermal deflection spectroscopy and detection [J]. *Appl. Opt.*, 1981, 20(8):1333-1344.
- [4] B. CH. LI, S. MARTIN, E. WELSCH. Pulsed top-hat beam thermal-lens measurement for ultraviolet dielectric coatings[J]. *Optics Letters*, 1999, 24(20):1398-1400.
- [5] Z. L. Wu, P. K. Kuo, R. L. Thomas, *et al.* Absorption measurement of thin films by using photothermal techniques: the influence of thermal properties[J]. *SPIE*, 1994, 2428:113.

### Brief professional biography of the author :

**Dr. HE Hong-bo** was born in Feb. 1971. He received his PhD degree of Optical Engineering from Shanghai Institute of Optics and Fine Mechanics (SIOM), Chinese Academy of Sciences (CAS) in July 1999. He had become an associate research professor since Jan. 2001 and was appointed to a position of research professor in Oct. 2004. His research interests include laser-induced damage behaviors, weak absorption test and process development of optical coatings, especially high power laser coatings.