Absorption measurement of optical thin films under high power density with a Closed Cavity

Xiaoting Fang (房晓婷), Shengfu Yuan (袁圣付)*, Wenguang Liu (刘文广),
Baozhu Yan (闫宝珠), and Bing Huang (黄 兵)

College of Optoelectric Science and Engineering, National University of Defence Technology,
Changsha 410073, China
**Corresponding author: shengfuyuan_bb@163.com*

Received September 4, 2014; accepted January 16, 2015; posted online February 26, 2015

A Closed Cavity measuring platform is built on the basis of a 1000 W-class direct current (DC)-discharge drived continuous-wave (CW) HF/DF chemical laser. On this platform, the absorption coefficients of optical thin films coated on the surfaces of monocrystalline silicon substrates, at the wavelength of 3.6–4.1 μm, is measured, when the power density on the surfaces of optical thin films reaches about 3.16 kW/cm^2. The measuring principle and structure of the Closed Cavity is introduced. The temperature curves and balanced temperature rises of the film-substrate systems under test measured through the experiment is presented in this Letter. The experiments show high reliability, good repeatability and strong practicality. The Closed Cavity measuring platform is applicable for not only absorption measurement but other performance measurement of optical thin films under high power density.

OCIS codes: 310.6860, 140.3070, 140.3330, 140.3460.
doi: 10.3788/COL201513.033101.

The development of high energy laser technology requires very high quality optical thin films, and the absorption loss of the optical thin films is one of the major factors that limit the development of high energy laser technology. Because absorption loss not only affects the optical quality of thin films, but also causes thermal deposition in the thin films. Especially for high power laser systems, even a weak absorption is sufficient to cause damage to optical coatings[1,2]. In order to detect and improve the quality of optical thin films, and to improve the damage threshold, lots of methods[3–9] have been used to detect the absorption coefficient of coating layers, but few can be used under high power density[10]. In this Letter, a Closed Cavity measuring platform is built on the basis of a 1000 W-class direct current (DC)-discharge drived continuous-wave (CW) HF/DF chemical laser, to detect the absorption coefficients of optical thin films under power density greater than 3 kW/cm^2. The balanced temperature rises of the film-substrate systems under test were measured through the experiment. After collecting and analyzing the data, the absorption coefficients of optical thin films coated on the surfaces of monocrystalline silicon substrates, at the wavelength of 3.6–4.1 μm, has been obtained. The 1000 W-class DC-discharge drived CW HF/DF chemical laser has been chosen as the laser source of the Closed Cavity platform because of its small scale, low gas consumption and long running time compared to large combustion drived lasers, and because of its high power density compared to other kinds of lasers, such as 10 W-class optical parametric oscillator lasers.

The Closed Cavity, which is used to generate the required power density to measure the absorption coefficient of the coatings, is diagramed in Fig. 1.

In Fig. 1, the resonator cavity is composed of two mirrors: L_R, the totally reflecting mirror, with the ideal reflectance of 100%; L_T, the output mirror with a transmittance of τ (quite small), $M_1 - M_4$ are the mirrors to be tested, they are placed in the resonator cavity of the laser source at different angles. M_1 and M_4 are 45° reflectors, M_2 and M_3 are 22.5° reflectors. P_{in} is the laser power "closed" in the cavity, and P_{out} is the output power. A is the size of output spot, I is the power density in the cavity. When working, the laser in the cavity is reflected back and forth by the reflectors (including 4 mirrors under test), then each film on the surfaces of mirrors under test is exposed to the power density of two beams of light: light spread forward I_+ and reversed I_-, which can be calculated as

$$I_+ = \frac{P_{\text{in}}}{A} = \frac{P_{\text{out}}}{\tau A}, \tag{1}$$

$$I_- = \frac{P_{\text{in}}}{A}(1-\tau) = \frac{P_{\text{out}}}{\tau A}(1-\tau). \tag{2}$$

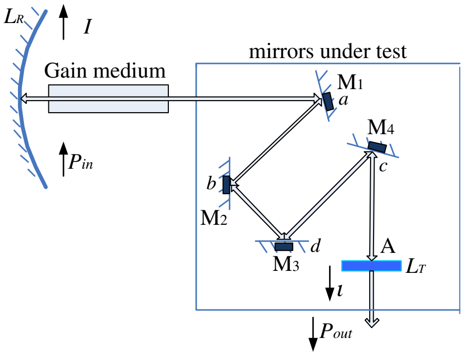

Fig. 1. Diagram of Closed Cavity platform.

The total power density on the surfaces of mirrors under test can be calculated as

$$I = I_+ + I_- = \frac{P_{\text{out}}}{\tau A}(2 - \tau). \tag{3}$$

Within a certain range, the output power P_{out} keeps falling with the decrease of the transmittance τ of the output mirror, while the laser power "closed" in the cavity P_{in} and the power density on the surfaces of $M_1 - M_4$ keep increasing. By measuring the output laser power P_{out}, the power density inside the cavity can be obtained. When I achieve the desired level (greater than 3 kW/cm^2), the Closed Cavity can be used to detect the absorption coefficient under high power density. *a, b, c,* and*d* are 4 groups of thermistors sticked on the back of the 4 film-substrate systems to measure temperature changes. Each group have 2 thermistors sticked on the left and top side of the back of mirror under test. The 8 thermistors are about 3 mm × 2 mm × 1 mm in size. The Closed Cavity platform can measure the absorption coefficient of four film-substrate systems simultaneously.

Essentially, the Closed Cavity platform is just an enclosed-end laser source, and its uniqueness lies in the requirement that the power density on the surfaces of the mirrors under test be greater than 3 kW/cm^2.

The physical picture of the Closed Cavity platform is showed in Fig. 2. The irradiation light source is a 1000 W-class DC-discharge drived CW HF/DF chemical laser with wavelength range of 3.6–4.1 μm. The mirrors under test are installed on the frames, which are isolated from the mirrors by insulating material to avoid heat transmission from mirrors to frames, thus to reduce measuring error. The mirrors together with the frames are closed in the vacuum Closed Cavity. An LP-3C laser power meter is adopted to monitor the output power, and the temperature change is measured by thermistors with temperature resolution of 0.1 K. The temperature data measured is collected and displayed in real time by a computer. The required balanced temperature rise can be obtained after data processing. The whole Closed Cavity platform is water cooled in the experiments.

When laser beams of high power density incident into the optical thin films on the surfaces of mirrors, part of the energy absorbed by the optical thin films transformed into heat, causing temperature rise of part of the optical films. The heat transfers to the adjacent substrate, causing temperature rise of the mirrors substrates. Stop the high energy laser irradiation, and wait for a while for the film-substrate systems to reach temperature equilibrium. After comparing the equilibrium temperature before and after high energy laser irradiation, T_1 and T_2, the equilibrium temperature rise of the film-substrate systems can be obtained as $\Delta T = T_2 - T_1$, then the heat absorbed can be calculated as

$$Q_0 = cm\Delta T, \tag{4}$$

and the absorption coefficient can be obtained as

$$\alpha = Q_0/Q, \tag{5}$$

where Q_0 is the absorbed heat, m and c stand for the mass and specific heat ratio of the film-substrate systems under test, respectively, ΔT is the equilibrium temperature rise of the film-substrate systems, and Q is the total heat on each surface of mirrors under test, which can be obtained as

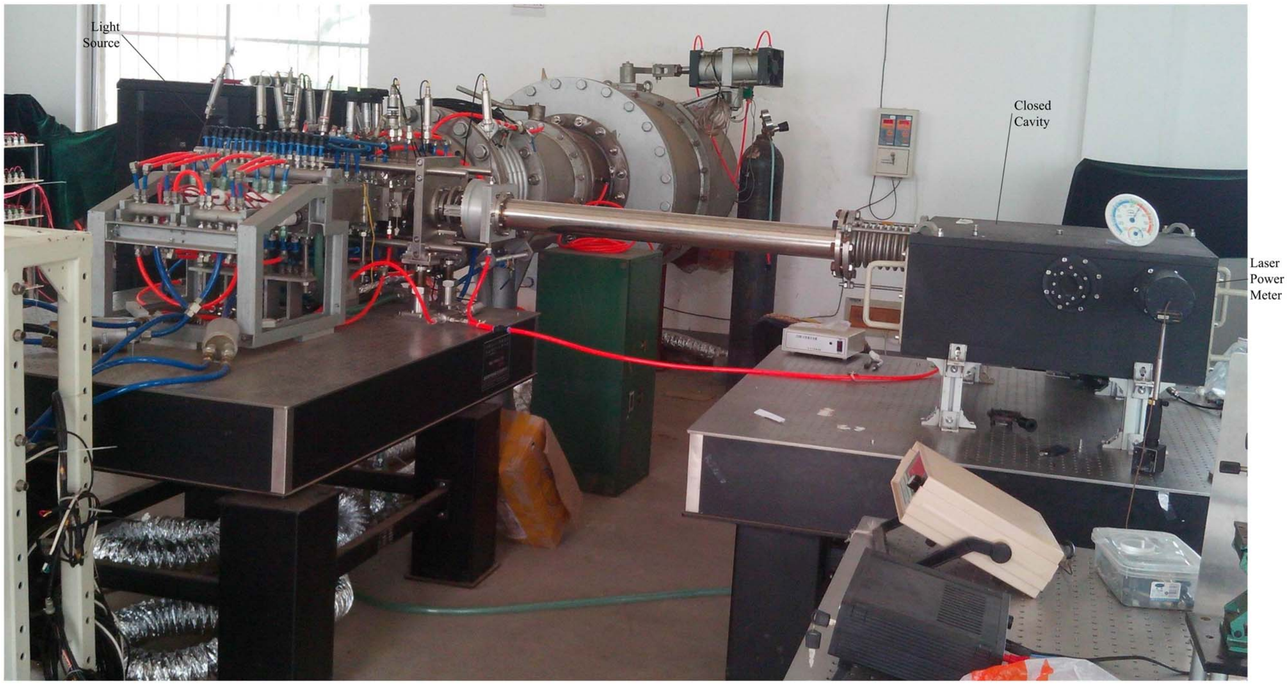

Fig. 2. Physical picture of the Closed Cavity platform.

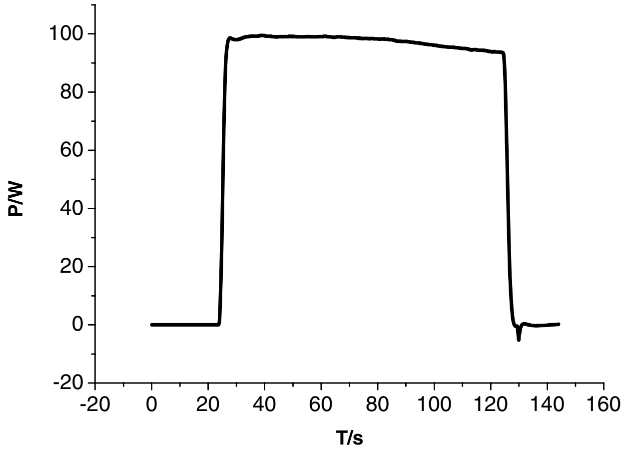

Fig. 3. Diagram of the output power curve.

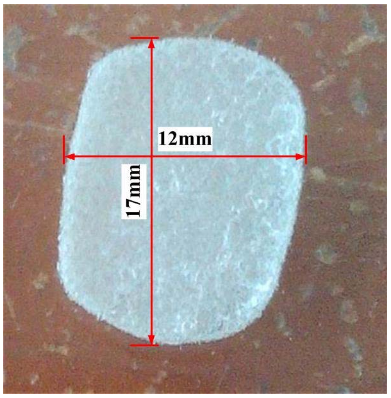

Fig. 4. Diagram of the ablation spot of the output laser X axis is the direction of flow.

$$Q = l \times a \times t. \tag{6}$$

Substitute I with Eq. (3), then the absorption coefficient of optical thin films under certain power density can be obtained as

$$\alpha = \frac{mc\Delta T \cdot \tau}{P_{\mathrm{out}}(2-\tau) \cdot t}, \tag{7}$$

where P_{out} stands for the output power, t is the running time of the laser, and τ is the transmittance of the output mirror.

The experiment is carried through in the Closed Cavity with a vacuum of about 100 Pa. The mirrors under test are monocrystalline silicons with the size of Φ50 mm. A double module DC-discharge drived CW HF/DF chemical laser is used as the radiation source of the Closed Cavity platform. Data for laser operating conditions are given below: 400 mm long discharge tubes; 286 mm long laser cavity; a total reflector with a 5 m radius of curvature and 3% coupling white jewel mirror with a 25 mm radius; power supply of $(3.2\ \mathrm{kV}, 110\ \mathrm{mA}) \times 12$. By proper “tuning” of gas composition, electric discharge power, and optical cavity, the maximum output power of about 99.5 W was achieved, and gas mass flow rates were listed below.

$$\dot{m}_{\mathrm{D}_2} = 0.0867\ \mathrm{g/s},\ \dot{m}_{\mathrm{NF}_3} = 0.7939\ \mathrm{g/s},\ \dot{m}_{\mathrm{He}} = 0.3528\ \mathrm{g/s},$$

in which NF_3 is the fluorine source gas, He is the main diluent in discharge tubes, and D_2 is the fuel gas. The flow mass of different fuels were metered by critical flow venturi (CFV) nozzles.

The laser kept working for 100 s in the experiment, the average output power of about 98.3 W was achieved at about 10 mm downstream of the nozzle exit plane. The total energy of the output is about 98296 J. Power density on the surfaces of mirrors under test was about $I = 3.16\ \mathrm{kW/cm^2}$, which met the requirement of greater than $3\ \mathrm{kW/cm^2}$. This laser output power is not optimized because of power supply capacity limitation.

The output power curve is shown in Fig. 3.

The $2.04\ \mathrm{cm^2}$ (17 mm × 12 mm) ablation spot of output laser is shown in Fig. 4. The laser beam size on the

Table 1. Absorption Coefficients Measurement Results.

Lenses	M_1	M_2	M_3	M_4
Size (mm)	Φ50	Φ50	Φ50	Φ50
Substrate	monocrystalline silicon	monocrystalline silicon	monocrystalline silicon	monocrystalline silicon
Optical thin film	multilayer dielectric film	multilayer dielectric film	multilayer dielectric film	multilayer dielectric film
Specific heat ratio (J/(g × K))	0.71	0.71	0.71	0.71
Reflectance	~99.9%	~99.9%	~99.9%	~99.9%
Mass (g)	18.059	13.384	18.174	18.178
Running time (s)	100	100	100	100
Equilibrium temperature rise (K)	4.79	10.16	5.08	4.01
Absorption coefficient (ppm)	95.1	149.6	101.6	80.2

surfaces of mirrors under test inside the cavity is about the same with the output laser.

When power density on the surfaces of mirrors under test in the Closed Cavity reached about 3.16 $\mathrm{kW/cm^2}$, the absorption coefficients of 4 optical thin films coated on the surfaces of 4 monocrystalline silicon substrates, at the wavelength of 3.6–4.1 μm, were measured. The same experiment was performed three times under the same conditions, and the measurement results are shown in Table 1.

In conclusion, using a Closed Cavity platform built on the basis of a 1000 W-class DC-discharge drived CW HF/DF chemical laser, the absorption coefficients of optical thin films coated on the surfaces of 4 monocrystalline silicon substrates, at the wavelength of 3.6–4.1 μm, is measured, under the power density of about 3.16 $\mathrm{kW/cm^2}$. The equilibrium temperature rise of the film-substrate systems under test are measured and recorded, by analyzing which, ideal results are obtained. The Closed Cavity platform can measure the absorption coefficients of 4 optical thin films at the same time. In the subsequent experiments, the influence of more detail factors, such as power density, laser beam intensity distribution, experimental vacuum, substrate material, size and surface cleanness, on the absorption coefficient of optical thin films, will be further explored. The Closed Cavity measuring platform is applicable for not only absorption measurement but other measurements, such as the measurement of wavefront deformation and thermal lensing effect[11].

This work was supported by the National Natural Science Foundation of China under Grant Nos. 10304025 and 10974255.

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