Options for polarization of probe beam in photothermal detuning technique

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An explicit model from the matrix method is utilized to describe the measurement sensitivity of the photothermal detuning technique dependent on the polarization of the probe beam. Numerical results show that the optimal probe wavelengths and the slope of the main spectral band edges are different for both s- and p-polarized beams with the same incident angle. Compared with the random polarized probe beam at the larger incident angle, the measurement sensitivity can be improved approximately twice over with the p- and s-polarized probe beams under the optimal condition.

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Absorption loss of optical components plays an important role in high power laser applications. In recent years, substantial progress has been made in the fabrication of ultralow absorption thin films. Optical coatings with absorption loss at the sub-parts per million (ppm) level have been prepared with ion-beam sputtering technique. To develop optical coatings with ultralow absorption loss, it is essential to develop sensitive absorption measurement techniques capable of measuring such low absorption. Various photothermal techniques have been developed to measure the absorption of optical coatings[1]. Laser calorimetry[2], the current international standard for the absorption measurement, has sub-ppm sensitivity and is capable of measuring absorbance at the parts ppm level. On the other hand, photothermal deflection[3], photothermal displacement[4], and surface thermal lens[5] have the sensitivity of tens of parts per billion (ppb) level, and are widely used for absorption mapping of optical coatings[6].

Photothermal detuning (PTDT), a novel photothermal technique, was reported for the absorption measurement of optical thin films[7−9]. This technique utilizes the spectral shift of optical coatings caused by absorption-induced temperature rise to measure the absorption of optical films. Temperature-induced spectral shift can be used to measure absorption when the temperature variation is due to the absorption of the laser beam energy by the optical coating. Figure 1 shows the reflection spectra of a high-reflection (HR) coating at the temperature T_0 and $T_0+\Delta T$. When the temperature T_0 changes to $T_0+\Delta T$, the reflection spectrum moves towards a longer wavelength. This temperature change causes a reflectivity change of the HR coating in a certain wavelength range. As shown in Fig. 1, the reflectivity change is at maximum (in the next segments, the corresponding wavelength is called optimal wavelength) around the edges of the main reflection spectral band of the HR coating. By measuring the reflected or transmitted power change of a probe beam with a wavelength (left edge at $\lambda =$ 500 nm and right edge at $\lambda =$ 663 nm) located near the edges of the reflection band, the temperature change of the HR coating can be indirectly measured, and the absorption of the HR coating that causes the temperature change can be determined. The application of PTDT technique is, therefore, limited to optical coatings with large temperature coefficient of reflectivity such as HR coatings or narrowband filters with sharp spectral edges. It is worth mentioned that for absorption measurements of optical coatings, the sensitivity of the PTDT technique is largely determined by the temperature coefficient of reflectivity. At the optimal probe wavelength and optimal incident angle, the temperature coefficient of reflectivity is proportional to the slope of the reflectivity with respect to wavelength at the edges of the main reflection spectral band. The sharper the spectral band edges, the higher the temperature coefficient of the reflectivity, and the higher the measurement sensitivity of the PTDT technique.

To detect the maximum spectral shift induced by the temperature change in the PTDT technique, the wavelength of the probe beam must match the optimal wavelength corresponding to the maximum spectral shift. In some cases, a probe laser with a wavelength close to the optimal wavelength can be first selected, and the spectral band of the optical coating can be shifted to match the optimal wavelength to the probe laser wavelength by adjusting the incident angle of the probe beam. It is known that the reflection and transmission spectra of optical coatings exhibit strong polarization effects[10] when used at larger oblique incident angles of the probe beam, as shown in Fig. 2. Meanwhile, for the complex structure coatings, compared with the s- and p-polarized average light, the reflection spectrum of the random polarized average light becomes more complex at the spectral band edge region. Hence, it is difficult to optimize measurement when the probe beam is random polarized light in the PTDT technique. Polarized light can be used to reduce this difficulty as the polarization of the probe beam has an effect on the measurement. In this letter, an explicit

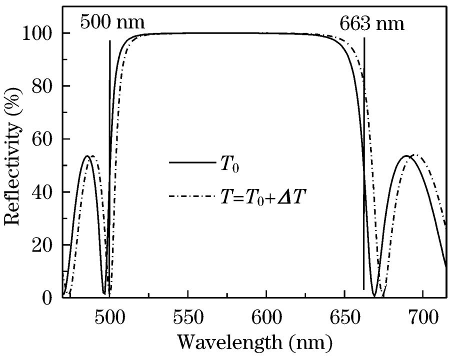

Fig. 1. Reflection spectra of HR coating at the temperatures T_0 and $T_0+\Delta T$, at the incident angle of 0°.

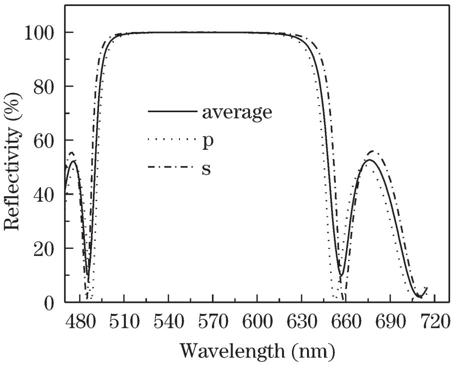

Fig. 2. S-, p-polarized, and random polarized light reflection spectra of a HR coating at the incident angle of 20°.

model is developed to describe the optimal wavelength and the slope of the reflection spectral band edge dependent on the polarization of the probe beam. Dependence of the measurement sensitivity on the polarization of the probe beam is investigated in detail.

If the refractive index and the physical thickness of the layer are represented as n_{f}^{T} and d_{f}^{T}, respectively, at the temperature T[11], the characteristic matrix[7] of the layer is

$$[M_j]=\left[\begin{array}{cc}\cos\delta_j & \frac{\mathrm{i}}{\eta_j}\sin\delta_j\\ \mathrm{i}\eta_j\sin\delta_j & \cos\delta_j\end{array}\right], \qquad (1)$$

where j is the layer number, η is the optical admittance (when light is incident on the film with an oblique angle, the s- and p-polarized beams are treated separately[10]), and δ_j is the optical thickness of the layer at oblique incidence, wlich is given by

$$\delta_j=\frac{2\pi}{\lambda}n_{\mathrm{f}}^{T}d_{\mathrm{f}}^{T}\cos\varphi_f, \qquad (2)$$

where φ_{f} is the angle of refraction of the layer, and λ is the probe beam wavelength.

For a multilayer coating, the reflection or transmission spectrum can be calculated by multiplying all the matrices of the layers of the multilayer. The resultant characteristic matrix $\mathbf{M}$ for the multilayer at the temperature T can be given by

$$\mathbf{M}=\begin{bmatrix}B\\C\end{bmatrix}=\begin{bmatrix}\cos\delta_1 & \frac{\mathrm{i}}{\eta_1}\sin\delta_1\\ \mathrm{i}\eta_1\sin\delta_1 & \cos\delta_1\end{bmatrix}\begin{bmatrix}\cos\delta_2 & \frac{\mathrm{i}}{\eta_2}\sin\delta_2\\ \mathrm{i}\eta_2\sin\delta_2 & \cos\delta_2\end{bmatrix}$$
$$.....\begin{bmatrix}\cos\delta_j & \frac{\mathrm{i}}{\eta_j}\sin\delta_j\\ \mathrm{i}\eta_j\sin\delta_j & \cos\delta_j\end{bmatrix}\begin{bmatrix}1\\N_{\mathrm{b}}\end{bmatrix}. \qquad (3)$$

The reflection spectrum of the multilayer can be calculated by

$$R(\lambda,T)=\left(\frac{N_0B-C}{N_0B+C}\right)\left(\frac{N_0B-C}{N_0B+C}\right)^{*}, \qquad (4)$$

where N_0 and N_{b} are the optical admittances of the air and the substrate, respectively.

The resulting reflection or transmission spectrum is a function of the wavelength, the incident angle, and the temperature. The slope of the reflection spectral band edge is obtained by differentiating the reflectivity R with respect to the optimal wavelength λ , that is,

$$\frac{\mathrm{d}R}{\mathrm{d}\lambda}=\frac{\partial R(\lambda,T)}{\partial\lambda}. \qquad (5)$$

The optimal wavelength for the PTDT technique and the corresponding slope of the main reflection spectral band edges at the incident angle can be determined.

The example used in this letter is a standard quarter-wave multilayer HR coating with an [air|(HL)^{10}H|BK7] design at a central wavelength of approximate 570 nm, and with 2.13 and 1.46 as the high- and low-refractive indices, respectively. The reflection or transmission spectrum of an optical coating moves towards the shorter wavelength when the incident angle increases. Figure 3 shows the optimal wavelength versus the incident angle for the HR coating. The optimal wavelengths for s- , p-polarized, and random polarized probe beams at the right (Fig. 3(a)) and left (Fig. 3(b)) edges of the reflection spectral band are presented. Optimal wavelengths at the incident angle of 27.5° are listed in Table 1. According to Fig. 3 and Table 1, the optimal wavelengths of the p-polarized and random polarized probe beams remain nearly the same. For the s-polarized light, when the incident angle increases, the reflection spectral band becomes broader. Therefore, the optimal wavelengths of the s-polarized light are shorter and longer than that of the s-polarized light at the left and right edges of the main reflection spectral band, respectively.

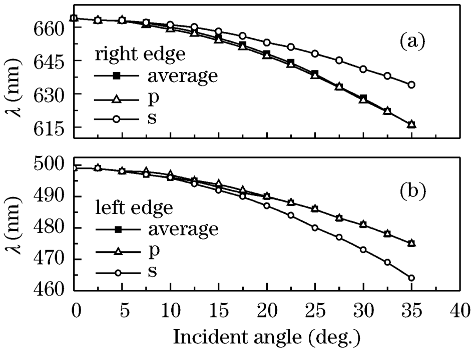

Fig. 3. Optimal probe wavelength versus the incident angle of the probe beam at the (a) right and (b) left edges of the main reflection spectral band.

Table 1. Optimal Wavelengths at the Incident Angle of 27.5°

Polarization	p		s		Average	
Band Edge	Left	Right	Left	Right	Left	Right
Optimal Wavelength (nm)	483	633	477	645	483	633

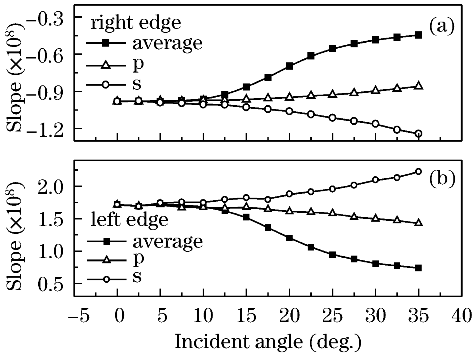

Fig. 4. The slope of the main reflection spectral band edge versus the incidence angle.

Table 2. Slope of the Main Reflection Spectral Band at the Incident Angle of 27.5°

Polarization	p		s		Average	
Band Edge	Left	Right	Left	Right	Left	Right
Slope ($\times 10^8$)	1.523	–0.915	2.02	–1.14	–0.876	–0.516

At the optimal probe wavelength, the slopes of the main reflection spectral band's left and right edges share the same incident angle, as shown in Fig. 4. The slopes of s- , p-polarized, and random polarized probe beams at the right (Fig. 4(a)) and left edges (Fig. 4(b)) of the main reflection spectral band are presented. Compared with the slope of the edges of the p-polarized light, the corresponding slope of the edges for random polarized light greatly decreases as the incident angle increases, especially at the larger incident angle region. On the contrary, for the s-polarized light, the slope of the edges increases with increasing the incident angle. The slope of the edges of the random polarized light is always smaller than the corresponding slope of the edges of the s- and p-polarized light. Hence, the measurement sensitivity can be improved in the PTDT technique, when the probe beam is s- or p-polarized light. Table 2 shows the slope of the edges at the incident angle of 27.5° with the optimal wavelength. The measurement sensitivity is proportional to the slope of the edges of the reflection spectral band. The sharper the spectral band edges, the higher the measurement sensitivity. According to Table 2, compared with the random polarized probe beam at the incident angle of 27.5°, the sensitivity measurement can be improved approximately 1.8 times and twice over with the p- and s-polarized probe beams, respectively.

In conclusion, the PTDT technique has been proven theoretically and experimentally to be a simple and sensitive technique for measuring the absorption of coated optical components. The results show that polarization of the probe beam has an effect on the measurement. The optimal probe wavelengths and the slope of the main spectral band edge are different for both s- and p-polarized beams with the same incident angle. Compared with the random polarized probe beam at the larger incident angle (for example, the probe beam is incident on the film with an oblique angle of 27.5°), the sensitivity measurement can be improved approximately twice over with the p-and s-polarized probe beams under the optimal condition, respectively. The simulation results provide a theoretical basis for analytical applications where the detection sensitivity is of the utmost importance.

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