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# CIRCULARLY POLARIZING MIRRORS FOR HIGH-POWERED LASERS

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**Abstract**, In this paper, the circular polarizing mirrors for high power lasers have been theoretically and experimentally studied, the circular polarizing mirror coated with multiple-film, which could induce 90° phase retardation is prepared experimentally.

## I. Introduction

For a long time after high-powered lasers began to be used in industrial processing, only the power of the light beam was focussed to direct attention on the effect on processing speed and quality due to factors such as the following: light power, mode, spot dimensions after focussing, and supplementary gas. However, the effect of polarizing state on the laser beam was neglected. It is generally considered that during laser processing, the laser beam is incident normally at the surface of the workpiece material. There is no relationship on the light beam between the coupling size in material and the polarizing state of the light beam. In the early eighties, Olsen et al at the Denmark University of Technology discovered during laser machining this assumption of the laser beam incident at the material surface in the normal direction is true only in the initial state of interaction between light and material. Once a cut is formed, actually the light beam is incident at the workpiece surface in a grazing direction. On account of this, reflection and absorption of the incident laser energy by the material is intensely restrained by the laser beam polarizing state [1]. For example, during laser cutting or welding, there is inconsistency in cut or welding seam width in different directions, since the cut or the weld seam inclination are caused by the optical polarizing state. The optical polarizing state not only is an important factor that cannot be neglected in laser processing, but in many occasions the polarizing state is even the decisive factor. As shown in numerous experiments in the mid-eighties, circularly polarized light is the optimal light beam for such laser processing as cutting and welding. With application of circularly polarized light, not only can the processing speed be greatly increased for optimizing the processing quality, but also one can solve such processing problems that cannot be solved with other kinds of light beam.

The final key point in obtaining a high-powered circularly polarized laser beam is to prepare an optical circularly polarizing mirror. In the article, the theoretical calculation and experimental preparation of the circularly polarizing laser mirror is the main subject.

## II. Theoretical Analysis and Calculations

The best route for obtaining high-powered circularly polarized lasers is as follows: by using a reflective polarizing element in the laser resonant cavity, let the laser have as its output linearly polarized light without reducing efficiency and power. Then the circularly polarizing mirror is applied to convert linearly polarizing light into circularly polarized light, at basically the same power. Here, the function of the circularly polarizing mirror is like a quarter-wave lens. As used in industrial processing at present, generally the laser is operated in the infrared waveband, with optical power over 500W. At present, we are unable to find an infrared material that can withstand the high power and also has the function of birefringence. Therefore, we are not able to apply the transmission type quarter-wave lens in high-powered infrared laser devices. Thus, a reflective apparatus of multilayer thin film structure was proposed [2]. In this article, this apparatus is referred as a circularly polarizing laser mirror. In the following discussion, the theoretical design and preparation of the circularly polarizing mirror used for a high-powered laser device with its center wavelength at 10.6μm are discussed. The design principle and preparatory method are suitable for other circularly polarizing mirrors with different center wavelengths.

The design requirements of the circularly polarizing mirror are as follows: when the incident angle is $\Theta=45^{\circ}$ ($\Theta_0$ is the incident angle in actual practice). By an appropriate arrangement, the linearly polarizing light is dissolved at the mirror surface into two mutually perpendicular vectors, the S-wave and the SP-wave. The oscillation amplitudes of these two waves are equal, as are the frequencies, but the phase difference is zero. Secondly, after reflecting the light upon passing through the thin-film circularly polarizing mirror, two components of the emerging light basically maintain the same oscillation amplitude and the amplitude at incidence. Between the S-wave and the P-wave, the phase delay difference $\Delta\phi$ is $\pm 90^0$ (if no discrimination is made on the left- and right-handed rotations, enter $90^0$ instead). Thus, actually there is no energy loss basically for the emerging light, which is circularly polarized light.

We can clearly see from the above-mentioned requirements that an ideal circularly polarizing laser mirror should satisfy two necessary conditions:

1. With respect to the reflectivities $R_S$ and $R_P$ of the S-wave and P-wave caused by the mirror surface, both reflectivities are basically the same and approach 1. In other words, .

2. The difference between phase delay $\phi_S$ and $\phi_P$ (due to the S-wave and the P-wave at the mirror surface), the $\Delta\phi$ should be $90^0$. In other words, $\Delta\varphi = \varphi_s - \varphi_p \approx 90°$。 Due to technical reasons, there is a certain difference between the actual optical thin devices and the real values.

The structure of the circularly polarizing mirror is as follows: the substrate lens is monocrystalline Si. The material for the substrate film is Au or Ag. The materials of the medium film are $BaF_2$ and ZnSe. The number of medium film layers are even, with materials of alternating high and low reflectivities. In contact with metallic lining film is a layer of low reflective material. In this research, the number of medium film layers was, respectively, 10, 12, and 14. When the number of layers is higher, the reflective band of $\Delta\phi$ in the vicinity of $90^0$ is wide. However, for too high a number of layers, the reflectivity is lowered due to absorption and scattering.

The fundamental formulas and symbols for theoretical calculation of the circularly polarizing mirror film system are the same as in reference [3]. The characteristic matrix of the film system is:

$$\begin{pmatrix} B \\ C \end{pmatrix} = \prod_{j=1}^{K} \begin{pmatrix} \cos\delta_j & \frac{i}{\eta_j}\sin\delta_j \\ i\eta_j\sin\delta_j & \cos\delta_j \end{pmatrix} \begin{pmatrix} 1 \\ \eta_{k+1} \end{pmatrix} \qquad (1)$$

For the S-wave and the P-wave, the phase thickness of the film layer is

$$\delta_j = \frac{2\pi}{\lambda} N_j d_j \cos\theta_j \qquad (2)$$

The refractive angle $\Theta_i$ is determined by the refractive law. The admittance $\eta_j$ is determined by the following equation:

$$\eta_j = \begin{cases} N_j\cos\theta_j & \text{S-wave} \\ N_j/\cos\theta_j & \text{P-wave} \end{cases} \qquad (3)$$

In the equation, $N_j$ is the refractivity of the material for the film of the j-th layer. Consideration is given to absorption and the metallic lining film; generally $M_i$ is a compound number. For multilayer medium film and metallic lining layer, the compound admittance Y=C/B. Thus, the reflectivity of the circularly polarizing mirror film system is

$$R = \left(\frac{\eta_0 B - C}{\eta_0 B + C}\right) \left(\frac{\eta_0 B - C}{\eta_0 B + C}\right)^* \tag{4}$$

and the reflective phase delay is

$$\varphi = \operatorname{arctg}\left[ \frac{i\eta_0 (CB^* - BC^*)}{(\eta_0{}^2 BB^* - CC^*)} \right) \tag{5}$$

In the equations, $\eta_0$ is the equivalent admittance of the incident medium. By using Eqs. (4) and (5), the corresponding values of the S- and P-waves are calculated. Then $R_S$, $R_P$, $\phi_S$, and $\phi_P$ can be obtained. Then the phase shift difference is obtained from $\Delta A\phi = \phi_S - \phi_P$.

The purpose sought for in a circularly polarizing laser mirror is to have high reflectivity and an appropriate phase shift difference. Therefore, a significant feature is that the film layer is not the thickness of the quarter-wave lens; each layer is different, without any cyclic property. Thus, great difficulties arise in calculating and preparing the film system so that a high-powered circularly polarizing laser mirror becomes one of the most complex and most difficult optical thin film devices.

The film system of the circularly polarizing mirror is designed automatically by using the optimal method with a computer. Select the optical thickness of the j-th layer as $f_j \cdot \lambda_0/4$; $f_i \in (0, 1.2)$. This is called the thickness coefficient of the j-th layer. $\lambda_0$ is the center wavelength (for a $CO_2$ laser, this is 10.62μm). The purpose of the calculation is to find a set of $\{f_i\}$ under the conditions of a given number of thin film layers and thin film material; thus, in the wavelength region near $\lambda_0$, the film system has high reflectivity and a phase difference of $90^0$. Thus, the following evaluation function is formed:

$$F = \sum_{\lambda} \left[ 1 - \frac{1}{2} (R_s + R_p) + \frac{|\pi/2 - |\Delta\varphi||}{\pi/3} \right]^2 \quad (6)$$

When $R_s=R_p=1$, $\Delta\phi=\pm\Pi/2$ is true near $\lambda_0$. In Eq. (6), F=0. These are ideal states. The actual problems is to set of $\{f_i\}$ so that F has a minimum value. In the article, the least squares method for the nonlinear damping is applied to treat this optimization problem. In the attached table and figure, there are typical f values of three sets of circularly polarizing thin film mirror systems calculated while the substrate film layer is Ag, and the relationship curve between the phase shift difference and the wavelength for the film system of the 14th layer. An error analysis can be made with a computer. As indicated in calculations, when the errors of film thickness and refractivity are ±1%, the error of $\Delta\phi$ is ±5%. When the errors of film thickness and refractivity are both ±2%, the error of $\Delta\phi$ is ±12%.

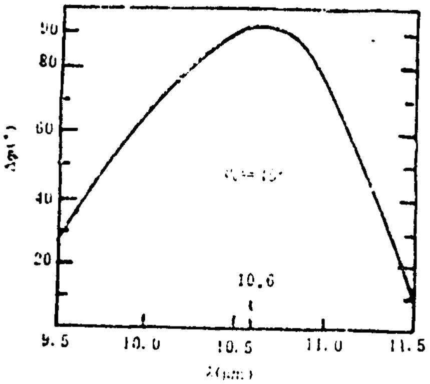
## ATTACHED TABLE: CALCULATED VALUE OF THICKNESS COEFFICIENT f FOR VARIOUS LAYERS OF LASER CIRCULARLY POLARIZING MIRROR

| [a] 膜层序号 | 10层[b]镜f值 | 12层镜f值[c] | 14层镜f值[d] |
|---|---|---|---|
| 1 | 0.713 | 0.724 | 0.742 |
| 2 | 0.694 | 0.708 | 0.714 |
| 3 | 0.586 | 0.588 | 0.596 |
| 4 | 0.741 | 0.752 | 0.763 |
| 5 | 0.783 | 0.791 | 0.806 |
| 6 | 0.857 | 0.863 | 0.872 |
| 7 | 0.932 | 0.934 | 0.936 |
| 8 | 0.931 | 0.956 | 0.962 |
| 9 | 0.958 | 0.967 | 0.968 |
| 10 | 0.964 | 0.968 | 0.972 |
| 11 | | 0.983 | 0.991 |
| 12 | | 0.987 | 0.993 |
| 13 | | | 1.080 |
| 14 | | | 0.996 |

REMARK; The substrate film layer is Ag; the first layer is exposed to the atmosphere.

KEY: a - number in film layer sequence b - f value of the mirror for 10th layer c - f value of the mirror for the 12th layer d - f value of the mirror for the 14th layer

After the error of $\Delta \phi$ exceeds ±10%, the practical value of the circularly polarizing mirror becomes significantly degrading. Therefore, in the preparatory process, the errors of film thickness and refractivity should be controlled within ±2%. This requires conducting precise measurements on birefringence and precise control of film thickness in the experiments.



Attached figure. Relationship curve between phase shift difference Δø and wavelength λ for the 14th mirror layer.

## III. Experiments and Results

The experimental results on circularly polarizing laser mirrors is divided into two parts: film coating and measurements. The film coating equipment involves remodeling the DMDE-450 optical multilayer film coating machines. The major improvements included the installation of a quartz crystal oscillation IC6000 film thickness monitoring instrument for monitoring random physical thickness in the appropriate locations within the vacuum chamber. From calculation analysis, the key to the experiment is precise control and measurement of film thickness and refractivity. For precise control of film thickness, a method combining the optical polar value and the crystal oscillation was adopted. By using a higher-order method, first the crystal oscillations are checked. Then the real-time monitoring of crystal oscillations is applied. In practice, first the method of optical polar value is applied to continuously coat 40 polar values on a material with the same control lens. Thus, the correlating relationship between optical thickness and the physical thickness (exhibited by crystal oscillations) is obtained. After such checking, the crystal oscillation thickness monitoring instrument can be used in real-time monitoring for films of any thickness. This method has an apparent advantage: between adjacent film layers in the polar values method automatic compensation can be made on the monitored wavelength, thus avoiding the error caused by the variation in molecular compensation property. By using coating 40 polar values on a material, even if the error of the final polar value is 10%, the relative error of the coated film layer is only 0.25%. This amounts to an upgrading by more than one order of magnitude in control precision over the conventional optical polar value method. This method produces excellent effects for film coating of high difficulty, and it is very advantageous in automating films is accomplished by the elliptical polarizing instrument of high precision.

The performance measurement of the fabricated circularly polarizing laser mirror was conducted on line with a high-powered $CO_2$ laser device. Let the output light beam from the $CO_2$ laser device pass through a polarizer to become linearly polarized light with its polarizing direction at a $45^0$ angle to the horizon. Then after reflection from the coated circularly polarizing mirror, the reflected light is analyzed with a polarization detection mirror. By measuring the power values at different polarization detection angles, the values of $\Delta\phi$ and R can be calculated. These are relative measurements. As indicated in analysis, the errors of $\Delta\phi$ and R values caused by such relative measurements are, respectively, within $\pm 2^0$ and ±1%. The comprehensive test results of testing the circularly polarizing laser mirror studied in the article are as follows: reflectivity $R=(R_S+R_P)/2 \geqslant 98\%$ ; the phase shift difference $\Delta\varphi=\varphi_S-\varphi_P=90° \pm 7°$; and the power density that can be tolerated is $I \geqslant 1000 W/cm^2$. These three parameters can satisfy all the present requirements on a circularly polarizing mirror with laser industrial polarizing.

The research utilized current technique, equipment, and materials in China. For the first time, circularly polarizing laser mirrors at the advanced international technical level of the late eighties were prepared. This will have an active function in promoting China's laser processing to be among the function in promoting China's laser processing to be among the world's advanced ranks.

In a brief introduction to the authors, Chen Qingmin is a male, born in May 1953. He is a professor holding a doctorate. Currently, he works in research on laser physics, solid-state physics, and optical thin films. Zhou Fengqing, male, was born in November 1962, He is a lecturer with a master's degree. Currently, he engages in research on optical thin film and laser technology. Li Xiaoping, male, was born in April 1962. He is an engineer with a master's degree. Currently, he engages in research on optical thin films and laser technology. He Yonggui, male, was born in August 1945. As a senior engineer, currently he engages in research on laser technology. Wang Jinhua, female, was born in December 1939. As a senior engineer, she currently engages in research on optical testing technology.

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