Transparent Waveplate (Retarder) of ZnSe for High Power CO_2 Lasers

Hirohito NISHI*, Hiromi IWAMOTO, Naoyuki UJIIE and Kunimitsu YAJIMA

Laser processing machines are utilized in various industrial applications such as cutting, welding and drilling. To improve their performance and avoid unstable processing caused by reflected laser beam from processed work, a $\lambda/4$ waveplate (phase retarder) is required. The phase retardation mirrors (circularly-polarized mirrors) have been used conventionally, but there are severe constraints such as a polarization azimuth angle and an angle of incidence of linearly polarized beam in designing beam delivery systems. We have developed a new transparent ZnSe $\lambda/4$ waveplate by adopting prism shaped substrates and optimized optical coating films free from above constraints. The developed waveplate for 9.6-micrometer laser has a transmittance of 98.0% and phase shift of 87.6 degrees, and the practicability of the 400-watt continuous wave CO_2 lasers are confirmed. Moreover, it contains no thorium or cadmium, it is exempt from regulations for radioactivity and RoHS. Our newly developed waveplate is expected to be utilized in various fields.

Keywords: CO_2 laser, ZnSe, waveplate, phase retarder

1. Introduction

Laser beam processing is in practical use in diverse fields since it is applicable to metal, ceramic and various other materials to perform a variety of precision machining operations including cutting, welding and drilling. In line with the recent trend for high-power oscillators in laser processing machines and improved beam quality, demand has been high for precise control of laser beams with optical elements.

We have developed and launched low-absorption thorium-free coated lenses to meet the trend for higher-power CO_2 laser machines. These lenses have gained wide acceptance among laser machine manufacturers and other users.(1), (2)

Our recent development is a transparent phase retarder (waveplate) for CO_2 lasers, which, using zinc selenide (ZnSe) substrates, facilitates the downsizing of laser beam delivery systems, while ensuring a low absorption.(3) The merits of a transparent waveplate include simplification of the beam delivery system by eliminating the need for adjusting the azimuth of polarization and the angle of reflection, which is a requirement for conventional reflective circularly polarizing mirrors.(4) In comparison with conventional transparent waveplates that use cadmium sulfide (CdS) or other infrared transparent crystals, the newly developed waveplate that uses low-absorption ZnSe substrates is suitable for higher-power laser beams. Moreover, as it contains no thorium or cadmium, this waveplate is free of radioactivity and thus easily complies with RoHS regulations.

2. Need for Polarization Control and Conventional Techniques

2-1 Polarization and processing characteristics

Laser oscillators generally output a linearly polarized beam. A laser beam used for cutting or the like always produces a concave molten pool on the surface of the workpiece, as shown in **Figure 1**.

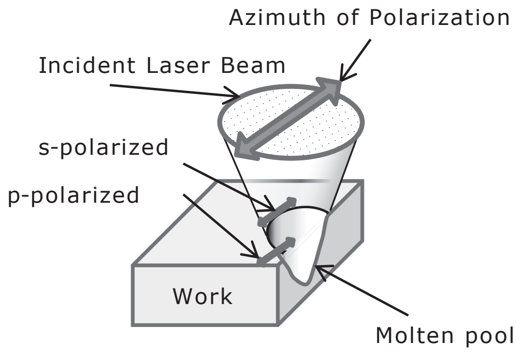

Fig. 1. Incident laser beam and its polarization

Oblique incidence of the radiated laser beam to the slope of the molten pool results in some circumferential positions of the opening receiving an s-polarized beam while others receive a p-polarized beam. In this phenomenon, different degrees of reflection occur according to the azimuth of polarization, as shown in **Figure 2**.

As a consequence, machining precision decreases. For example, the cutting kerf is subject to variation depending on the cutting direction, as shown in **Figure 3**, and drilled holes become elliptical. To prevent these problems, a circularly polarizing mirror or waveplate is inserted in proximity to the laser beam output aperture of the oscillator to convert the linearly polarized beam into a circularly polarized beam.

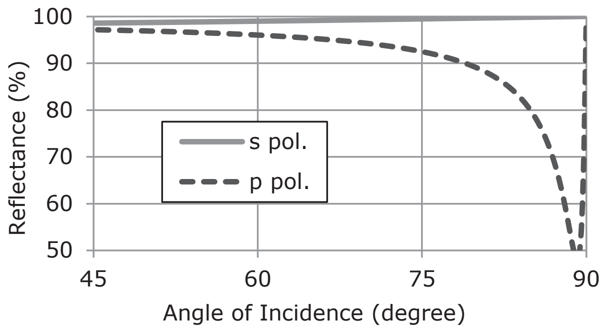

Fig. 2. Reflectance of Al surface dependent on angle of incidence

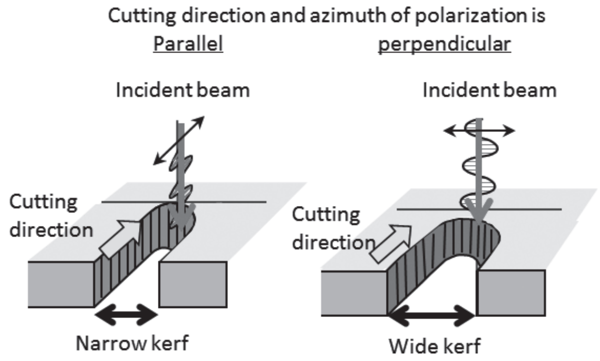

Fig. 3. Cutting width dependent on azimuth of polarization

2.2 Elimination of return beams reflected from workpiece

If the reflection of a workpiece is high against laser beams, the workpiece, when laser machined, reflects the laser beam as a return beam. If the return beam travels back and reaches the oscillator through the laser beam delivery system, the oscillator may be damaged or the oscillation output may become unstable. The return beam is therefore eliminated in the sequence described below and illustrated in **Figure 4**.

1) A p-polarized laser beam enters and exits a polarizer that is transparent to p-polarized beams and reflects s-polarized beams.
2) The phase of the p-polarized beam exiting the polarizer is shifted by 90 degrees by a $\lambda/4$ phase shift element ($\lambda/4$ waveplate or circularly polarizing mirror) to be converted into a circularly polarized state and the beam irradiates the workpiece.
3) Part of the circularly polarized beam incident on the workpiece is reflected and becomes a circularly polarized return beam (in the reverse direction of rotation) with its phase being shifted by 180 degrees.
4) The phase of the return beam is shifted again by 90 degrees by the $\lambda/4$ phase shift element and is incident on the polarizer in an s-polarized state.
5) Since the polarizer reflects s-polarized beams, the return beam from the workpiece is eliminated and does not travel back to the oscillator.

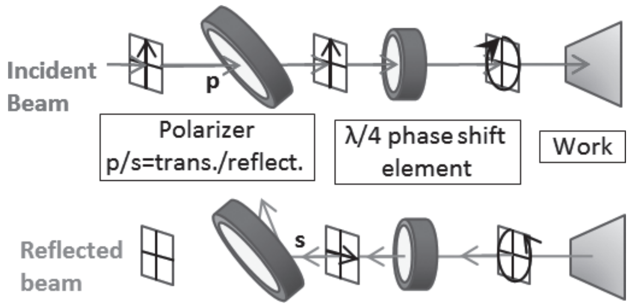

Fig. 4. Typical process to eliminate reflecting laser beam from work piece

2-3 Conventional $\lambda/4$ phase shift optics for CO_2 Laser

High-power CO_2 laser processing machines have conventionally used a circularly polarizing mirror. A circularly polarizing mirror requires that both the azimuth of polarization, ψ, of the incident beam and the angle of incidence, θ, be 45 degrees, as shown in **Figure 5**.[4] Consequently, difficulties associated with a circularly polarizing mirror include design constraints of the optical delivery system that guides the laser beam from the oscillator to the workpiece and complicated optical axis adjustments that are required for the optical system.

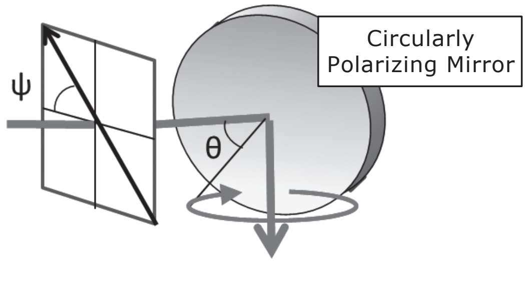

Fig. 5. Circularly polarizing mirror and adjustment of incident beam

In comparison, the azimuth of polarization of the incident beam of a transparent waveplate is adjusted simply by rotating the waveplate around the optical axis, facilitating the design of the optical delivery system and optical axis adjustment. To make transparent waveplates, CdS or other birefringent crystals have been used. The transmission phase shift, Δ, is expressed by the following equation:

$$\Delta = 2\pi \cdot (n_s - n_f) \cdot d / \lambda \quad \cdots\cdots (1)$$

where, n_s is the slow-axis refractive index, n_f is the fast-axis refractive index, d is the thickness of the crystal, and λ is the wavelength of the incident beam. Accordingly, it is possible to adjust the phase shift Δ by controlling the thickness of the crystal d. Waveplates fall into zero-order waveplates with $0 \leq \Delta < 2\pi$ (= 360°) and high-order waveplates with $2\pi \leq \Delta$. A zero-order waveplate would make an ideal waveplate with low wavelength dependence. However, its crystal thickness must not exceed several tens of micrometers, which is difficult to fabricate. Consequently, a generally accepted solution is to lay a piece of a birefringent material over another piece so that their crystal axes become orthogonal to each other in order to control the phase shift through the difference between their thicknesses.[5]

Conventional transparent waveplates for CO_2 lasers include those made of CdS or other birefringent crystals. Their drawbacks are that they are not suitable for high-power lasers due to their substantial absorption of CO_2 laser beams and that it is not possible to grow them into a large crystal.

3. Design and Fabrication of Transparent Waveplates

We designed and fabricated a waveplate, imposing the requirements that the waveplate should be transparent to simplify the optical delivery system, suitable for high-power lasers, and compatible with such lasers' typical beam diameter of approximately 30 mm, as summarized below.

Low-absorption ZnSe, which is used to construct optical elements for high-power CO_2 lasers, is an ideal material. However, on an "as is" basis, it cannot be used to make a waveplate since it is not a birefringent material. As a solution, we decided to generate a phase shift by forming an optical coating on the surface of the material. It is known that to control phase shift with optical coatings, an oblique incidence must be set up so that the resultant phase shift after exiting an optical coating is in accord with the polarization state of each beam.[6] We therefore used a prism-shaped substrate (wedge) with the angle of inclination α, as shown in **Figure 6**.

The angle of inclination α and the output angle β of a ZnSe substrate are determined by the following equation according to Snell's law of refraction, which uses the refractive index n of the substrate.

$$n \cdot \sin \alpha = \sin \beta \quad \cdots\cdots (2)$$

To design the waveplate, the output angle β was set to 45 degrees considering the diameter of the induced laser beam, the required thickness of the ZnSe material, and the design difficulty in optical coatings.

By substituting the refraction index (n = 2.409) of ZnSe at wavelength 9.6 µm and the output angle β of 45 degrees into **Equation (2)**, an angle of inclination α = 17.1° is obtained.

In accordance with this result and using the pitch polishing technique, we fabricated two ZnSe wedges 45 mm in diameter and 17.1 degrees in the angle of inclination.

The nornmal-incidence side of the wedge was provided with an anti-reflection coating formed by ion-assisted deposition using ZnSe as a high-refraction index material and fluoride as a low-refraction index material, as with low-absorption lenses.[1] The inclined side was provided with a multi-layer coating (14 layers) designed with a commercially available software package (TFCalc, Software Spectra, Inc.). The multi-layer coating was formed using the same coating materials and techniques used for the anti-reflection coating to achieve a transmission phase shift of 45 degrees (= $\lambda/8$) at the angle of incidence, within the substrate, of 17.1 degrees and an output angle of 45 degrees and to exert an anti-reflection property.

When passing through one wedge, a laser beam exits it at β = 45°, as shown in **Fig. 6**. In light of this, using a stainless steel spacer to create an air gap between them, we point-symmetrically overlaid two wedges provided with the same optical coatings and secured them in an aluminum mount 65 mm in outside diameter and 18 mm in thickness, as shown in **Figure 7**. The aperture of the mount was set to 40 mm in diameter.

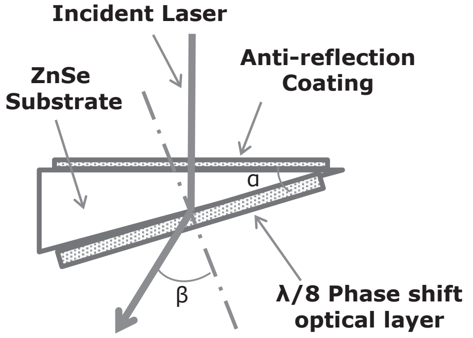

Fig. 6. Basic component made of prizm-shaped ZnSe

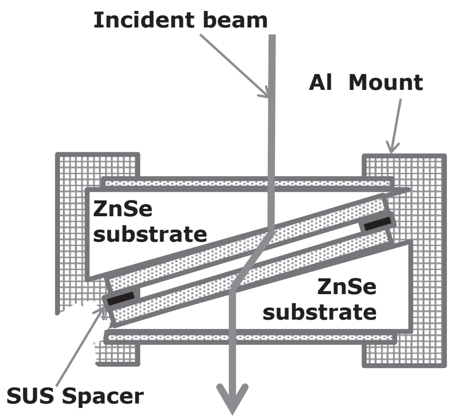

Fig. 7. Structure of developed waveplate

This waveplate allows incident beams to exit almost coaxially, albeit slightly offset due to the thickness of the air gap. Since one wedge shifts the phase of the exiting beam by 45˚ by virtue of the optical coating, two wedges shift the phase of the exiting beam by 90˚.

4. Fabrication Results

4-1 Infrared transmittance and absorption

Using an infrared spectrophotometer (IR-700, JASCO Corporation), the infrared transmission spectra of the waveplate shown in **Fig. 7** were measured. **Figure 8** shows the measurement results.

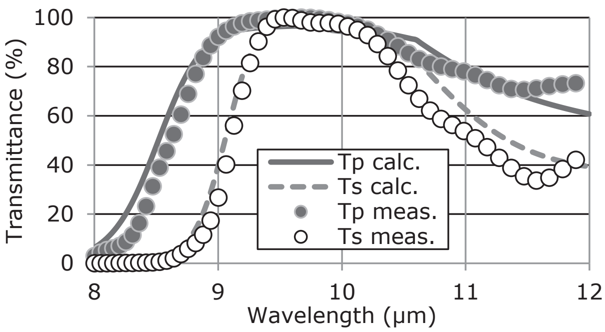

Fig. 8. Transmittance spectrum of obtained waveplate

The transmittance was 98.0% at the target wavelength of 9.6 μm. It is surmised that the optical coatings were formed as designed since the calculated and measured spectra closely agree with each other in terms of the proximity of the target wavelength. The measurements show substantial differences from the calculated values on the longer wavelength side. This is interpreted as resulting from two causes: the design assumed that at the air gap, the output angle and the angle of incidence would be consistently 45 degrees and increased absorption would occur due to the thickness of the ZnSe substrates.

On the basis of the 98.0% transmittance at 9.6 μm and the total reflectance of 1.3% of the four optical coatings calculated from the coating design, the absorption of the waveplate is estimated to be less than 1%.

4-2 Transmission phase shift

The transmission phase shift spectra of the above-discussed unit were measured with an infrared ellipsometer (IR-VASE, J.A. Woollam Co.). **Figure 9** shows the measurement results. The transmission phase shift was 87.6 degrees for the target wavelength of 9.6 μm. The measured spectra for transmission phase shift compared favorably with the calculated values.

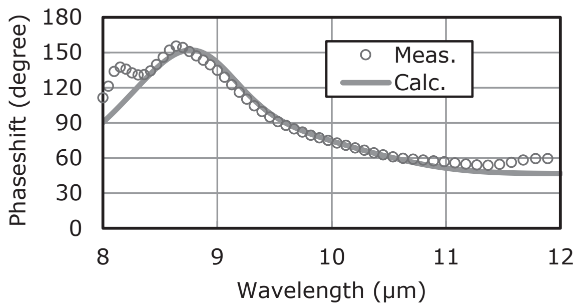

Fig. 9. Transparent phase shift spectrum of obtained waveplate

4-3 Other properties

Irradiated with the beam of a 400 W continuous wave CO_2 laser (wavelength: 10.6 μm), the constructed waveplate caused no damage or other problems, although its temperature somewhat increased.

Control of visible light transmittance by the optical coatings formed on the waveplate was not taken into consideration when designing the waveplate. However, the visible light transmittance (wavelength: 535 nm) of the waveplate was approximately 40%, as shown in **Photo 1**. This implies the advantage that use of a visible light will make alignment easy when using the optical system in practice.

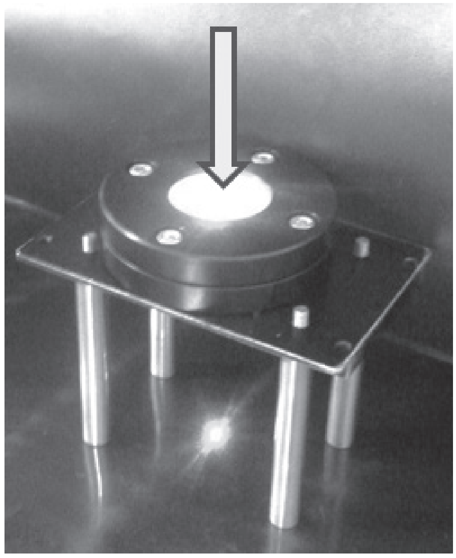

Photo 1. Appearance of 535 nm laser transmitted through developed waveplate

We inserted the constructed waveplate into an actual laser machine for evaluation. The waveplate continually exhibited the required performances.

5. Conclusion

A waveplate made of ZnSe substrates was constructed for high-power lasers. **Table 1** shows the properties of the waveplate. Each property has been verified to be suitable for practical use.

Table 1. Properties of the developed waveplate

Properties	Planned Values	Actual Values
Transmittance	> 96%	98.0% at 9.6 μm
Transmittance Phase Shift	90±10˚	87.6˚ at 9.6 μm
Laser Power Durability	400 W	> 400 W
Mount Size	---	Diameter 65 mm Thickness 18 mm (Clear Aperture 40 mm)

This report has discussed a $\lambda/4$ waveplate for 9.6 μm laser. By revising the design of the optical multi-layer coating, it will be possible to adapt the waveplate to other CO_2 laser wavelengths such as 10.6 μm and 9.4 μm and fabricate $\lambda/2$ or $\lambda/8$ waveplates. Future tasks include developing an increased variety of phase-controlling optical elements with improved performance for wider application of laser machines and improvements in machining performance.

• TFCalc is a trademark or registered trademark of Software Spectra, Inc.

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