Optical isolator for pulsed fiber lasers

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Optical isolators are required for high power pulsed fiber lasers to block reflected light from objects being processed. Fujikura has realized an isolator using $Tb_3(Sc,Lu)_2Al_3O_{12}$ (TSLAG) single crystal as the Faraday rotator for the first time. In this paper, we report unique features of the TSLAG single crystal and typical optical quality of the isolator.

1. Introduction

Pulsed fiber lasers are required further optical output power because they are expected to expand applications, such as engraving, scribing for patterning, micro welding and micro cutting[1)]. It is important for the lasers to block reflected light from objects being processed because this reflected light causes lasing instability and damage to laser components. Therefore, an optical isolator is necessary to prevent incident reflected light from reaching the pulsed fiber lasers.

Optical isolators have been utilizing since the beginning of optical communication networks. Therefore, structures and operation principles of optical isolators are well known, with a Faraday rotator is considered as one of the most important parts for the isolators. In optical communication networks, ferromagnetic garnets, such as $Y_3Fe_5O_{12}$ (YIG), have been utilized as a Faraday rotator because they have large Verdet constant and relatively high transparency in the 1.3-1.55 µm wavelength range. However, it is impossible for pulsed fiber lasers to employ ferromagnetic garnets due to optical absorption in the 1 µm wavelength band. Therefore, highly transparent garnets in the 1 µm wavelength band have been needed for a long time. Currently, $Tb_3Ga_5O_{12}$ (TGG) is widely used as a Faraday rotator owing to increasing of demands for 1 µm wavelength band pulsed fiber lasers. However, it remains a challenge for the TGG to grow large bulk crystals due to misbalance of own ion radii. $Tb_3(Sc,Lu)_2Al_3O_{12}$ (TSLAG) is one of the most promising materials to overcome the issue because its ion radius balance is much superior than that of the TGG. In addition, it is possible to downsize an isolator because Verdet constant of the TSLAG is larger than that of TGG.

Fujikura has realized an isolator using TSLAG single crystal for the first time. In this paper, we report unique features of the TSLAG single crystal and typical optical quality of this new isolator.

2. TSLAG single crystal

Fujikura has developed TSLAG single crystal as a Faraday rotator in collaboration with National Institute for Materials Science (NIMS)[2)]. A Faraday rotator works to rotate polarized light due to Faraday effect when magnetic field is applied to light propagation direction. Verdet constant is defined as the polarization rotation angle per unit light pass length and unit magnetic flux density. It means larger Verdet constant enables downsizing of a Faraday rotator and/or a magnet in an isolator.

Figure 1 shows the crystalline structure of TSLAG. The garnet structure is described as $\{C_3\}[A_2](D_3)O_{12}$, where {C} is the octahedral site, [A] is the hexahedral site and (D) is the tetrahedral site. The ion radii of each cation composing TSLAG are shown in Table 1. TSLAG consists of Tb in the {C} site, Sc/Lu in the [A] site and Al in the (D) site; therefore, molecular formula is expressed as $Tb_3(Sc,Lu)_2Al_3O_{12}$. The key point of this composition is small difference between the ion

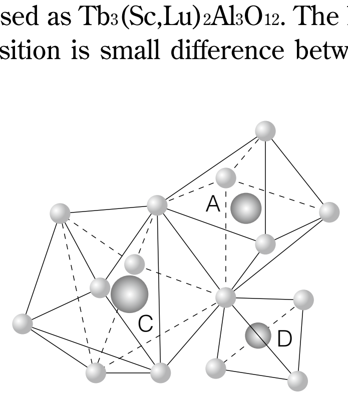

Fig. 1. Crystalline structure of TSLAG.

Table 1. Cations composing TSLAG crystal and their ion radii.

Coordination site	Element	Ion radius (Å)
{C} site (Octahedron)	Tb (Terbium)	1.04
[A] site (Hexahedron)	Sc (Scandium)	0.745
	Lu (Lutetium)	0.861
(D) site (Tetrahedron)	Al (Aluminum)	0.390

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Panel 1. Abbreviations, Acronyms, and Terms.

Faraday rotator
A Faraday rotator works to rotate polarized light due to Faraday effect when magnetic field is applied to light propagation direction. The Faraday effect is a magneto-optical phenomenon which is interacted between light and the magnetic field in a material.

Verdet constant
Verdet constant is an optical constant that describes the strength of Faraday effect for a particular material. It is given by
$V = \theta_f / l \cdot H$
where V is Verdet constant, θ_f is polarization rotation angle, L is path length and H is magnetic flux density in direction of light propagation.

Czochralski process
Czochralski process is one of the most popular methods of single crystal growth. It uses a seed crystal as the starting material and the seed crystal is introduced into high-temperature crystal melt. A bulk single crystal is formed by drawing up the seed crystal from the crystal melt.

AR coating—Anti-reflection coating
An AR coating is a type of optical coating applied to surfaces of optical crystals to reduce reflection.

radius of Tb in the {C} site and Sc/Lu in the [A] site. This superior ion radius balance enables us to grow large bulk crystals[2].

Fujikura has been growing TSLAG single crystals by Czochralski process. We have successfully fabricated large bulk TSLAG single crystals without macro cracks, as shown in Fig. 2. Table 2 shows Verdet constant comparison between TSLAG and TGG. When Verdet constant of TGG is 1.00 (a.u.), measured at 1080 nm and 22°C, the relative constant of 1.28 is obtained for TSLAG at the same measurement conditions. This result indicates the TSLAG enables downsizing of a Faraday rotator and/or a magnet compared with the TGG. Figure 3 shows transmission spectrum of a 10 mm-thick TSLAG single crystal without anti-reflection (AR) coating. High transparencies are observed not only in the 1 μm wavelength band but also in the visible wavelength range without around 500 nm. Therefore, it is possible to apply the TSLAG for various lasers, such as 1 μm wavelength band pulsed fiber lasers and visible lasers.

Fig. 2. Photograph of a TSLAG single crystal.

Table 2. Verdet constants of TSLAG and TGG crystals.

Crystal	Verdet constant (a.u.)
TGG	1.00
TSLAG	1.28

3. Optical isolator

Figure 4 shows a newly developed optical isolator using the TSLAG single crystal. This isolator can transmit 1 μm wavelength band light launched from a pulsed fiber laser with low attenuation and it can block reflected light from the objects being processed. Transmission loss of the laser light through the isolator is known as forward insertion loss and that of reflected light through the isolator is known as backward insertion loss. Isolation is defined as the ratio between the backward insertion loss and the forward insertion loss, and it is one of the most important optical parameters for isolators.

Table 3 shows typical properties of the Fujikura optical isolator for pulsed fiber lasers. This isolator has

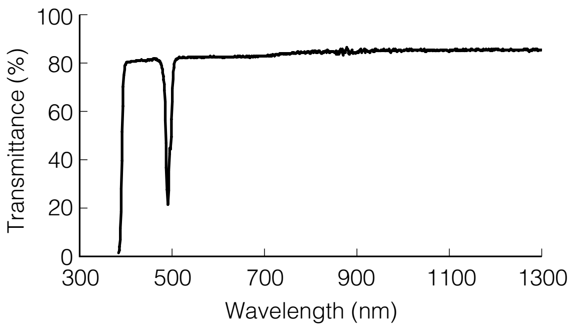

Fig. 3. Transmission spectrum of a TSLAG crystal.

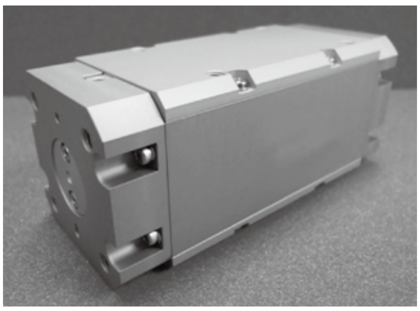

Fig. 4. photograph of a newly developed optical isolator.

Table 3. Typical properties of an optical isolator for pulsed fiber lasers.

Item	Typical property	Unit	Note
Center wavelength	1085	nm	Center wavelength can be customized to comply with specification of a fiber laser.
Forward output power	80	W	
Backward input power	40	W	
Forward insertion loss	0.1	dB	
Isolation	38	dB	

high power durability, such as 80-W forward output power from pulsed fiber lasers and 40-W reflected light power from objects being processed. Superior optical properties have also been achieved, such as low attenuation of 0.1 dB in the forward direction and high isolation of 38 dB.

An optical isolator consists of a single crystal Faraday rotator and some other optical crystals in its light path. These crystals are coated with AR layers on their optical surfaces. The crystals and/or the AR coatings will be damaged in some cases when high power density laser is input into the crystals. It causes increasing of forward insertion loss and degradation of output beam shape. Moreover, it may be possible to breakdown an isolator in the worst case. We investigated long-term continuous lasing operation to evaluate high power durability of crystals, including TSLAG. Figure 5 shows the optical output fluctuation of the optical isolator in continuous 2000-h operation. Average output power of 56 W was obtained without significant fluctuations during the 2000-h operation. Figure 6 shows comparison of output beam patterns before and after continuous 2000-h operation. The beam patterns were almost identical before and after operations. In addition, actual damage of the crystals and the AR coatings was not observed by microscope after the 2000-h operation. These results indicate Fujikura optical isolators have high reliability for high-power long-term lasing operation.

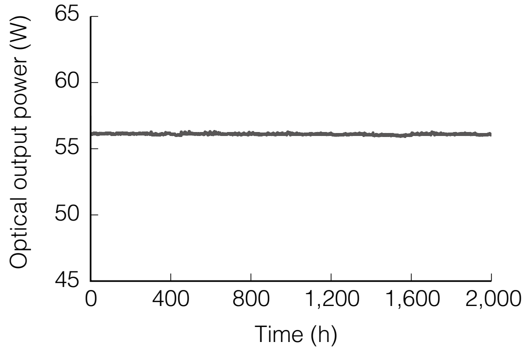

Fig. 5. Optical output fluctuation of an optical isotator in continuous 2000-h operation.

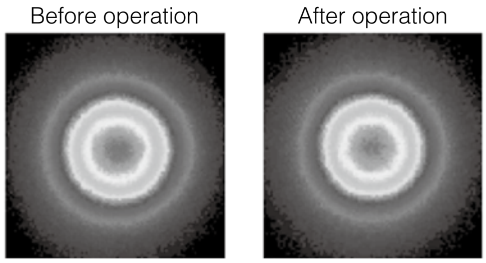

Fig. 6. Output beam patterns before and after continuous 2000-h operation.

4. Conclusion

Fujikura has realized an isolator using $Tb_3(Sc,Lu)_2Al_3O_{12}$ (TSLAG) single crystal for the first time, and it has been already utilized in pulsed fiber laser products. This isolator has superior optical properties and high reliability for high-power long-term lasing operations. Optical isolators will be applicable in a variety of fields with increasing optical output power of pulsed fiber lasers. Therefore, further development on the optical properties and reliabilities of optical isolators will be required in the near future.

References

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