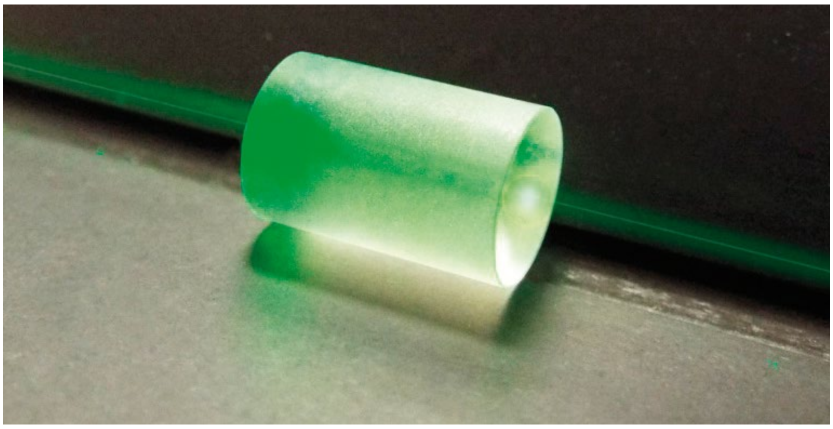
Promising Materials for High Power Laser Isolators

Growth of large single-crystals for Faraday rotator and isolator applications

Kevin T. Stevens, Wolfgang Schlichting, Gregory Foundos, Alexis Payne and Evan Rogers

Northrop Grumman Synoptics is developing the growth of large single-crystal fluoride materials for Faraday rotator / isolator applications. These materials exhibit smaller nonlinear refractive index and thermo-optic coefficients, while maintaining Verdet constants near those of the commonly used terbium gallium garnet (TGG) crystals. In particular, the cubic potassium terbium fluoride, KTF (KTb_3F_{10}) crystal has low absorption and thermo-optic coefficients. The crystal growth and performance of these single-crystal fluoride materials will be discussed as well as recent improvements to the performance of TGG crystals.



KTF crystals have a large transparency range similar to that of TGG and can be used in rotator and isolators for visible and near-IR wavelengths.

Optical isolators are critical devices to insure safe and predictable output in many commercial lasers for various applications. These isolators insure that the back-reflected laser beam does not re-enter the laser cavity by utilization of the non-reciprocal Faraday effect [1]. This magneto-optic effect is the rotation of the plane of polarization of a light beam as it is transmitted through a material in the presence of an external magnetic field that is coaxial with the light. The polarization rotation is in the same sense regardless of the direction of propagation of the light. When a Faraday rotator is combined with suitably aligned polarizers, the laser beam can pass in one direction only and optical isolation is achieved.

The optically active Faraday material is the key optical element in a high-performance optical isolator. Important characteristics in a Faraday optic element include a high Verdet constant, low absorption coefficient, low nonlinear refractive index, and high damage threshold. Short elements have a clear advantage because they minimize the effects of self-focusing and other thermal-related effects. The most commonly used material for the 650 – 1100 nm range is terbium gallium garnet (TGG –$Tb_3Ga_5O_{12}$). Key parameters for TGG include its cubic crystal structure for alignment-free processing, little to no intrinsic birefringence, and ease of manufacture. However, for high-power laser applications, TGG is limited by its absorption at 1064 nm and its thermo-optic coefficient, dn/dT. Specifically, thermal lensing and depolarization effects become a limiting factor at high laser powers. While TGG absorption has improved significantly over the past few years, there is an intrinsic limit.

Because of recent advancements in high-power fiber lasers, there is a need to either improve the performance of TGG crystals or develop alternative materials that can handle the increasing power levels. Improvements have been made so that consistently low-absorbing TGG crystals can be manufactured. Although these developments have led to better performance in high-power isolators, it is not enough. Therefore, other crystals such as the fluorides have been studied. It is well known that single-crystal fluorides have lower thermo-optic coefficients that are typically negative in value. In addition, these crystals exhibit lower nonlinear refractive indices [2]. Unfortunately, unlike the gallium garnets, the fluoride crystals are incongruently melting and therefore can be more difficult to grow, especially to the scale of oxides like TGG.

Company

Northrop Grumman SYNOPTICS
Charlotte, USA

Synoptics is the industry leader in the manufacture of solid-state laser materials and components for medical, defense, industrial and scientific applications. Having entered into the synthetic laser material business in 1965, SYNOPTICS continues to enhance and develop its manufacturing capabilities to meet the demands of customer needs. The company is a "one stop shop" with diverse skills and capabilities from crystal growth, fabrication, thin film deposition, inspection and packaging.

www.as.northropgrumman.com/synoptics

Improvements in the manufacture of TGG

Currently, terbium gallium garnet ($Tb_3Ga_5O_{12}$, TGG) is the most common single-crystal Faraday rotator used in optical isolator applications. Because TGG melts congruently at a temperature of ~ 1825 °C, large crystals can be grown using the Czochralski technique. Crystals up to 50 mm in diameter and 100 mm long are common. Although relatively large crystals of TGG can be grown, there are several bulk defects that limit full utilization of the boules. These defects include color centers, dislocations, inclusions, and strain areas due to the growth interface shape. Synoptics has invested resources to improve yields by eliminating or controlling the formation of such defects. In particular, color centers give rise to unwanted absorption and therefore limit performance in terms of thermally induced depolarization and overall transmission. Fig. 1 shows spectra from three TGG crystals with varying levels of absorption. The broad absorption throughout the visible spectral region are color-center related and can impact performance even in the near-infrared. TGG is most commonly used in isolators operating at 1064 nm and is therefore very sensitive to increase absorption at this wavelength. Typical absorption values at 1064 nm for TGG range from 0.20 to 0.30 % / cm. The color-center defects present in TGG arise due to unwanted impurities and variations in the growth atmosphere causing changes in the cation valence states. By understanding how these parameters affect color center formation, Synoptics has been able to decrease the absorption levels at 1064 nm to < 0.17 % / cm on a consistent basis. Crystal "C" in Fig. 1 shows the spectrum from a near-colorless TGG crystal that is approaching 0.15 % / cm absorption at 1064 nm.

Promising single-crystal fluoride Faraday materials

Because there are intrinsic limits to the performance of TGG, Synoptics is exploring alternative Faraday materials. In particular, two single-crystal fluoride materials first reported by Weber et al. [3] show great promise for use with higher power lasers. Both lithium terbium fluoride, TLF ($LiTbF_4$) and potassium terbium fluoride, KTF (KTb_3F_{10}) crystals exhibit small non-linear refractive indices and thermo-optic coefficients, while still exhibiting Verdet constants near those of TGG making them attractive materials. Unlike TGG, TLF and KTF melt incongruently and are therefore more challenging to grow. Since the growth is essentially flux-type, precipitate inclusions and scatter-type defects are present unless melt stoichiometry is carefully controlled. To date, large TLF crystals up to 4 cm in diameter and 7 cm in length have been grown with regions of scatter-free material. However, TLF has a tetragonal scheelite structure and therefore has a large intrinsic birefringence. This must be accounted for by precise crystallographic alignment of the laser beam propagation direction with the crystal optic axis (*c*-axis). Because of the stringent crystallographic alignment requirements with TLF, recent efforts have focused on KTF, which has a cubic crystal structure and no birefringence. Currently KTF crystals have been grown along the <100> and <111> orientations in sizes up to 3 cm in diameter and 4 cm in length. Multiple growth orientations have been attempted due to a natural <111> cleavage plane.

As shown in Fig. 2, both TLF and KTF have similar transparency ranges to TGG. It should be noted that the two fluoride materials show improved absorption at the shorter wavelengths. Unlike TGG, color center formation and cation valence changes are minimized in the fluoride crystals resulting in a consistent "water-white" appearance. This is promising for optical isolators for visible wavelength lasers.

Several KTF parts have been fabricated, polished and anti-reflection coated, for testing with Electro-Optics Technology, Inc. (EOT) which makes optical isolators utilizing TGG grown by Synoptics. Parts range size from 4 mm to 8 mm in diameter and up to 20 mm in length. Fig. 4 shows a sample of three fabricated KTF parts that are laser-polished and AR coated. EOT produces a variety of optical isolators that are increasingly becoming enabling components, allowing lasers to reach their full potential for materials processing, life sciences, and other scientific applications. Optical isolators for pulsed fiber lasers prevent back-reflections from work pieces that

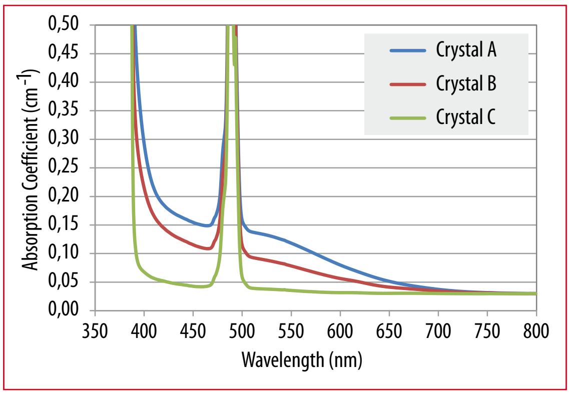


Fig. 1 Absorption spectrum for TGG crystals showing varying concentrations of color centers. The spectra have been converted to absorption coefficient (cm^{-1}) but not corrected for reflective losses.

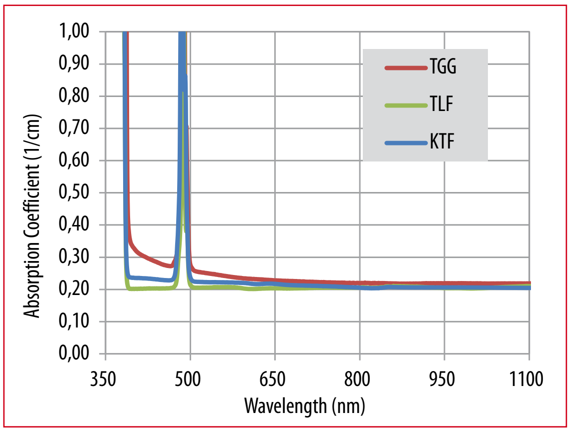


Fig. 2 Absorption spectra for three Faraday crystals: TGG, TLF, and KTF.

can couple into the fiber and damage the laser. Laser diodes (particularly single frequency laser diodes) require high levels of isolation to eliminate frequency instability caused by back reflections. Ultrafast lasers utilize optical isolators (particularly if amplified) to eliminate amplified spontaneous emission ASE and in some cases to prevent back-reflections from work pieces.

Advances in the power levels of ultrafast solid-state lasers and pulsed

Company

Electro-Optics Technology, Inc. (EOT)
Traverse City, USA

EOT is a worldwide supplier of enabling components and diagnostic equipment to manufacturers and users of high power laser systems. Current products include Faraday rotators and optical isolators for use with laser diodes, fiber lasers, solid-state lasers, and QCLs. The company remains committed to being an industry leader in innovative solutions to optical feedback, beam delivery, and pulse detection.

www.eotech.com

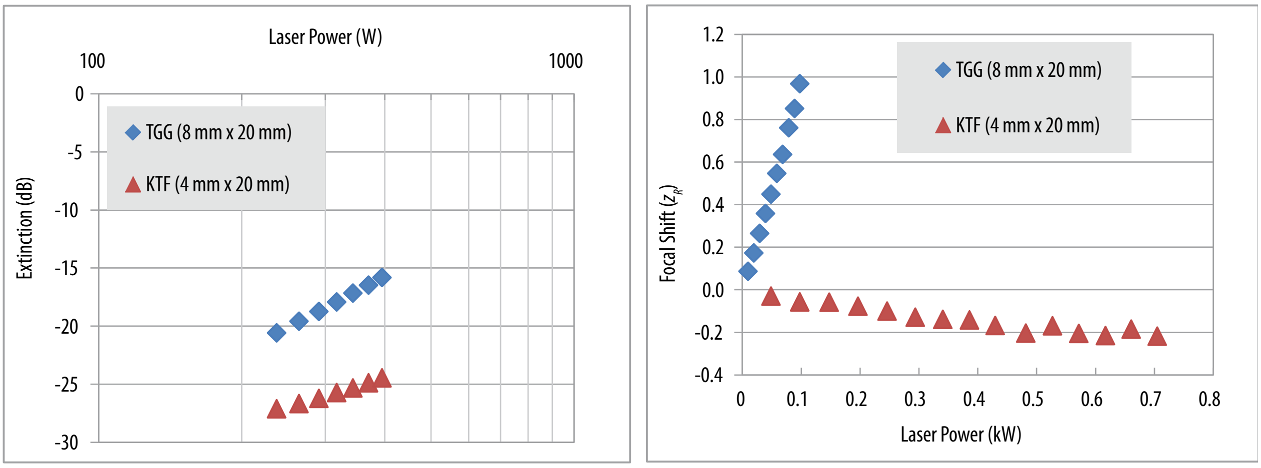
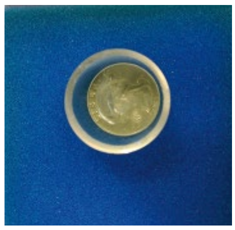


Fig. 3 Optical isolator performance for TGG and KTF as measured at Electro-Optics Technology, Inc.

Table 1 Summary of the diverse discussed crystals' properites

Composition	$Tb_3Ga_5O_{12}$ (TGG)	$TbLiF_4$ (TLF)	KTb_3F_{10} (KTF)
Crystal structure	cubic	tetragonal scheelite	cubic
Transparency range	400 – 1500 nm	400 – 1500 nm	400 – 1500 nm
Verdet constant (rad / T · m)	39	38	36
Refractive index (1064 nm)	1.944	n_o=1.4679, n_e=1.4962	~ 1.50
Density (g / cm^3)	7.2	5.46	5.86
Absorption @ 1064 nm	~ 0.16 % / cm	~ 0.02 % / cm	~ 0.02 % / cm
Thermo-optic coefficient (dn / dT)	1.79×10^{-5} / K	~ 1×10^{-6} / K	~ 1×10^{-6} / K
Nonlinear refractive index	~ 2×10^{-19} m^2 / W	~ 1×10^{-19} m^2 / W	~ 1×10^{-19} m^2 / W
Crystal Image	45 mm × 100 mm 	35 mm × 50 mm 	30 mm × 30 mm 

fiber lasers have placed increasing demands on optical isolators. Thermal lens focal shift, depolarization, and concerns over B integral all come into play at higher power levels. This is pushing the limits of current Faraday rotator materials and putting a premium on lower absorption, lower non-linear refractive index, and high pulsed damage threshold Faraday materials to accommodate these growing trends. The use of KTF is demonstrating such qualities and enabling the performance of optical isolators at power levels previously attainable only with significant design compromises.

Depolarization and focal shift have been measured at EOT for laser powers up to 400 Watts for an optical isolator utilizing KTF. Fig. 3 shows the results and include similar measurements made with a TGG isolator.

As demonstrated by EOT, KTF has reduced depolarization for higher laser powers and a smaller focal shift than TGG. These results are extremely promising and indicate that KTF could be a simple solution for optical isolators at the higher laser powers. Key properties of the discussed crystals are given in Table 1.

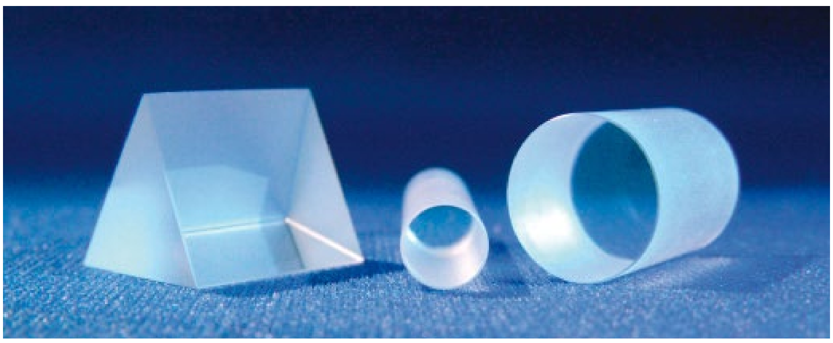


Fig. 4 Fabricated samples of KTF.

Conclusions

Recent improvements to the growth and manufacture of TGG crystals have led to cost effective and superior quality optical isolators for visible and near-infrared lasers. In addition to high quality TGG, advancements in the growth of other crystalline materials, such as TLF and KTF, will lead to improved optical isolation performance for higher power lasers. Recently measured thermo-optic coefficients for TLF show that these fluoride materials have very promising characteristics [4].

DOI: 10.1002/latj.201600017

[1] *E. Hecht*: Optics, 4th Edition, Addison Wesley (2002) 366

[2] *R. Adair* et al.: Phys. Rev. B **39** (1989) 3337 – 3350

[3] *M. J. Weber* et al.: J. Appl. Phys **49** (1978) 3464 – 3469

[4] *D. E. Zelmon* et al.: Applied Optics **55** (2016) 834 – 837

Authors

Kevin T. Stevens earned his Bachelor degrees in physics and mathematics from the College of Charleston and his doctorate in solid state physics from West Virginia University. During this 15-year tenure at Synoptics he has managed the Thin-Film Coating group, served as Director of Manufacturing, and is currently Director of Research and Development. Additionally, he is the Director of Production Crystal Growth and acting Facilities Manager. Dr. Stevens earned his MBA in 2010 from Queens University of Charlotte.

Wolfgang Schlichting manages New Business Development with focus on Europe for Northrop Grumman Synoptics. He studied physics at the University of Tübingen and received his M.Sc. degree in optical sciences from the University of Arizona with research focusing on laser systems and magnetic circular dichroism. Before joining Synoptics, he founded Wolf Research LLC and also worked for IDC, NPD and Reveo Inc. in the areas of optical data storage, photovoltaics and cholesteric liquid crystals.

Gregory Foundos R&D Engineer, Crystal Growth. Mr. Foundos has 35 years experience in melt growth of both oxide and fluoride crystals. He has worked extensively on garnets, perovskites, and sheelites. Mr. Foundos studied analytical chemistry at York Technical College and received a Bachelor of Science degree in business from Bellevue University.

Alexis Payne R&D Optical Engineer, Northrop Grumman Synoptics. Ms. Payne received her Bachelor's in physics from the College of Charleston in 2015. In her time at Synoptics, she has been involved with developing fabrication processes for both oxide and fluoride crystals. She is also developing processes for measuring and qualifying material.

Additional Author: **Evan Rogers, Technology Development Manager at Electro-Optics Technology (EOT)**

Wolfgang Schlichting, Northrop Grumman Corp., Aerospae Systems, SYNOPTICS, 1201 Continental Blvd., Charlotte, NC, USA, wolfgang.schlichting@ngc.com