Faraday Rotators With Short Magneto-Optical Elements for 50-kW Laser Power

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***Abstract*—Faraday rotators with short magneto-optical elements are created and experimentally studied. The magneto-optical elements are made three to four times shorter either by cooling them to nitrogen temperatures or by increasing the magnetic field. These ways are shown to increase maximum average laser power passing through the Faraday isolators up to 50 kW.**

***Index Terms*—Cryogenic chamber, depolarization, Faraday isolator, isolation ratio, liquid nitrogen, permanent magnets.**

I. Introduction

With the average power of repetitively pulsed and continuous-wave (CW) lasers steadily growing, the problem of improving optical devices becomes ever more important. A key requirement now is to compensate for thermally induced effects caused by light absorption. Among devices that are strongly affected by thermal self-action are Faraday isolators (FIs) and Faraday mirrors (FMs) due to relatively strong absorption in their magneto-optical elements ($\sim 10^{-3}$ cm^{-1}) [1]. The light absorption gives rise to such parasitic effect as thermally induced depolarization [2], which can significantly worsen the isolation ratio, which is the most important characteristic of FIs and FMs. The so-called "cold" depolarization occurs in magneto-optical elements because of imperfection of a medium, and nonuniformity of the magnetic field is typically small ($\sim 10^{-4}$). The depolarization caused by light absorption in the optical elements, the so-called "hot" or "thermally induced" depolarization, is dependent on the power of optical radiation. In high-power lasers, it greatly exceeds the cold depolarization and mainly determines the isolation ratio.

There are several approaches to reducing the thermally induced depolarization in magneto-optical elements of FIs and FMs. One way is to divide the optical element into thin discs cooled through the optical surface [3], [4]. This considerably decreases the transverse temperature gradient and, thus, the thermally induced depolarization in the discs. Another popular method [2], [5]–[10] is based on compensation of the thermally induced depolarization. In this approach, two Faraday elements and a reciprocal optical element placed between them is used instead of one Faraday element rotating the polarization plane by 45°. Here, distortions induced in the first element are partially compensated for in the second. Faraday rotators produced in this geometry provide reliable isolation at kilowatt-level powers of passing radiation [11], [12].

In this paper, we discuss a different approach to decreasing the thermally induced depolarization, which consists of shortening the magneto-optical elements themselves. As evident from the well-known expression for the angle of rotation of the polarization plane φ

$$\varphi = VHL \tag{1}$$

(where H is the strength of the magnetic field in magneto-optical element and L and V are the length and Verdet constant of the magneto-optical element, respectively), this shortening can be achieved in two ways—either by increasing the magnetic field or by cooling the magneto-optical element and, hence, increasing the Verdet constant [13]. For proper operation of FI and FM, it is essential to keep the angle φ unchanged and equal to 45° during one pass through the device.

In Section II, we describe experimental implementations of two FM variants with magnet systems based on superconducting solenoids. Due to the resulting increase in the magnetic field, we managed to considerably shorten the length of traditional magneto-optical elements made of glass MOC-04 [1] (analog: glass FR-5, Hoya, Japan) and TGG crystal. In Section III, we describe a cryogenic Faraday isolator with permanent magnets, which is a qualitatively new device in which both the magnets and the magneto-optical element are cooled to liquid nitrogen temperatures. In this case, shortening is achieved not only by increasing the Verdet constant [13], but also by increasing the magnetic field when magnets are cooled. Section IV is devoted to the study of possibilities for increasing the magnetic field through optimization of the magnet field of permanent magnets. In Section V, we discuss the results and prospects of creation of FIs operating at gigantic average powers up to 50 kW.

II. Shortening of Magneto-Optical Elements By Increasing the Magnetic Field: FMs With Superconducting Solenoids

Here, we describe FMs in which the magnetic field was significantly increased due to employment of superconducting solenoids instead of traditional permanent magnets.

A schematic of the experimental setup where we studied powerful-superconducting-solenoid-based FMs is presented in Fig. 1(a). CW linearly polarized radiation from a single-mode ytterbium fiber laser at 1076 nm (IPG Photonics) was used as heating and probing radiation simultaneously. Maximum power of the beam with a diameter of 3 mm was 50 W. Radiation from laser 1 was directed at a small angle onto an FM under

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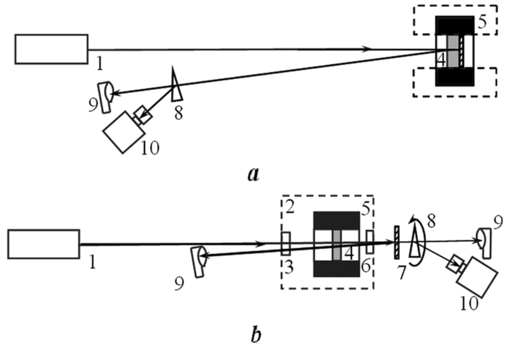

Fig. 1. Schematic of experimental setup. (a) FM with superconducting solenoids (b) Cryogenic FI. 1: ytterbium fiber laser; 2: cryostat; 3, 6: cryostat windows; 4: magneto-optical element; 5: magnet system; 7: mirror; 8: calcite wedge; 9: absorber; 10: power meter. Elements cooled to (a) helium and (b) nitrogen temperatures are shown by the dashed boxes.

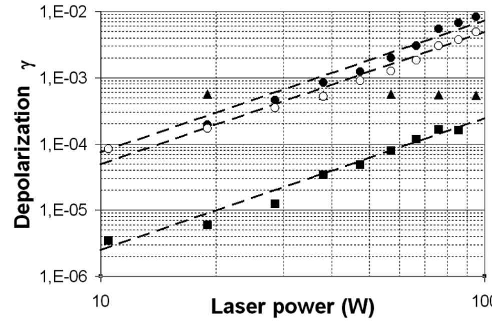

Fig. 2. Depolarization versus heating radiation power in FM with MOC-04 glass at beam diameters of 12 mm (triangles) and 3 mm (squares) and in FM with TGG crystal (circles) with heat removal through optical surface (open circles) and without any heat removal (solid circles). Dashed line indicates theoretical dependences for thermally induced depolarization $\gamma \sim P^2$.

study, which was comprised of a magneto-optical element 4 placed in the magnetic field of magnet system 5. The magnet system 5 was a cryostat with two cooling contours—with nitrogen and helium. The cryostat was put in direct contact with solenoids which were cooled to the superconducting state and thus generated magnetic fields of 50 kOe along their axes. A distinctive feature of the cryostat design is that the magneto-optical element at the solenoid axis is kept at room temperature. A multilayer dielectric window was coated on the back surface of the element 4 [see Fig. 1(a)]. Therefore, the laser radiation traveled two passes through the magneto-optical element, and the total power of heating radiation P varied from 0 to 100 W. Absorption-induced heating of the magneto-optical element led to depolarization of radiation, which was split by a calcite wedge 8. The main part of the radiation with power P_2 was directed to an absorber 9, and depolarized radiation with power P_1 went to a powermeter 10.

By depolarization γ, we understand the relation

$$\gamma = \frac{P_1}{P_1 + P_2} \tag{2}$$

and the isolation of the optical device I, measured in decibels, will be given by the relationship

$$I = -10 \cdot \lg \gamma. \tag{3}$$

It should be noted that, at the same parameters of laser radiation, γ may be totally determined by thermal effects and may be totally dependent on cold depolarization, depending on optical quality of the magneto-optical element. (The cold depolarization in Faraday rotators is also determined by nonuniformity of the magnetic field over the volume of the magneto-optical element; in all our magnet systems, it was $< 1\%$, which corresponds to $\gamma < 10^{-4}$).

In the first series of our experiments, we studied a MOC-04 sample with a length of 9 mm and a diameter of 23 mm. The dependences of the depolarization on heating radiation power for a beam with a diameter of 12 mm are shown in Fig. 2 (triangles). The isolation ratio in the rotator amounted to > 30 dB and almost did not depend on laser radiation power in the range up to 100 W and thus was totally determined by the cold depolarization of the magneto-optical element. The use of a beam with a smaller diameter of 3.2 mm allowed us to considerably lower the contribution of the cold depolarization. The isolation ratio was > 50 dB (see the squares in Fig. 2) for laser radiation powers of 10–20 W. With a further increase in laser power, the depolarization value grew according to $\gamma \sim P^2$ [2].

In the second series of experiments, we used a TGG crystal with [001] orientation, length of 3.5 mm, and diameter of 9 mm. Measurements were made also in the laser scheme shown in Fig. 1(a). This time, however, the magneto-optical element shortened due to the increased magnetic field allowed us to use disc geometry. As disc geometry, in contrast to traditional rod geometry, we understand a situation when the length of a magneto-optical element becomes comparable to or less than the incident beam diameter. Along with quantitative benefits (lower absorbed power), this geometry also offers a qualitative advantage of cooling the optical element through its optical surface (end sides). As a result, transverse temperature gradients, which are the main source of depolarization, are greatly reduced.

In the disc geometry ($L \ll r_0$, where r_0 is the beam radius), because of cooling through the optical surface, there occurs a strong dependence of the thermally induced depolarization on aspect ratio L/r_0 [3], [14], [15]

$$\gamma \propto P^2 \left(\frac{L}{r_0}\right)^4. \tag{4}$$

In TGG experiments we implemented two situations: without heat removal and with heat removal through optical surface of the crystal by placing the mirror surface of the magneto-optical element 4 in thermal contact with a metal disc. The diameter of the laser beam was 3.2 mm, so the aspect ratio was 0.6. The results of the experiment presented in Fig. 3 show that the value of thermal depolarization with heat removal (see Fig. 2, open circles) is smaller than without heat removal (see Fig. 2, solid circles) by 20%–30%, which is in agreement with experimental results [15] for this value of aspect ratio. (The fact that the depolarization value in TGG is higher than in MOC-04 is due to the use of a crystal with high absorption.)

III. Shortening of Magneto-Optical Elements Due to Cooling: Cryogenic FI

In the previous section, we described FMs with a non-cooled magneto-optical element, i.e., at room temperature

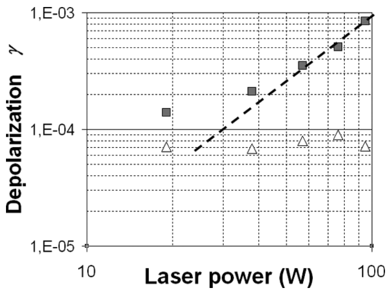

Fig. 3. Theoretical (dashed line) and experimental dependences of depolarization on power of heating radiation: in TGG crystal at room temperature (squares) and in cryogenic FI at 95 K (triangles).

$(T \sim 300$ K) and placed in a strong magnetic field. Here, we report the results of experiments on the creation of a cryogenic FI, in which the magneto-optical element and the magnet system comprised of permanent magnets, are cooled.

A. Increasing the Verdet Constant

Under cooling conditions, the Verdet constant of paramagnets considerably increases according to the formula [13]

$$V = \frac{\mathrm{const}}{T}. \tag{5}$$

Therefore, cooling to liquid nitrogen temperatures provides an opportunity to shorten the magneto-optical element several times. This is why, for creation of our cryogenic FI, we chose a TGG crystal with length as short as 3.2 mm instead of the 1.5-cm-long crystals used in room-temperature isolators.

The schematic of the experiment is shown in Fig. 1(b). Radiation from an ytterbium fiber laser 1 was used as heating and probing radiation. Through a fused silica entrance window 3, the beam is directed to a cryogenic FI, which is a vacuum cryostat 2 with a traditional permanent-magnet Faraday rotator inside. The cryostat 2 is a vacuum chamber in a cooling double vessel consisting of an inner vessel that is placed in direct thermal contact with the sample and an outer vessel that serves to additionally cool the inner vessel and to slow down evaporation of coolant so that the cooling process could be quasi-stationary. The cooling process is controlled by a calibrated copper thermal sensor. The cryostat comprises a Faraday rotator which in turn consists of a magneto-optical element 4 (TGG crystal with the [001] orientation, length 3.2 mm, and diameter 7.5 mm) and a magnet system 5. The angle of rotation of the polarization plane by this rotator at room temperature (293 K) was $\varphi_0 = 9.7^\circ$. The beam exits the cryostat through window 6 and falls onto a mirror 7 with transmission coefficient 0.5%. After being reflected off of the mirror, the main part of radiation returns to the cryostat, thus making its second pass through the element under study. Absorption-induced heating of the magneto-optical medium resulted in depolarization of the radiation. Part of the radiation transmitted through the mirror 7 is divided into two portions by a calcite wedge 8. The depolarized portion is directed to a powermeter 10, while the remaining portion passes to an absorber 9.

The dependences of the depolarization occurring in the sample on heating radiation power are shown in Fig. 3. It is evident that, at the room-temperature TGG crystal, the depolarization almost does not depend on laser radiation power up to 50 W, i.e., it is totally determined by the level of the cold depolarization in the crystal. At 60–100 W, hot depolarization becomes more significant, and experimental values of depolarization agree well with theoretical estimates [2], [6], [16] (see Fig. 3, squares). Fig. 3 also shows a dependence obtained at temperature $T = 95$ K (triangles). Note that, at lower temperatures, the depolarization decreases and is totally determined by the level of cold depolarization in the given point of the crystal. The isolation ratio of the cryogenic FI is not less than 40 dB.

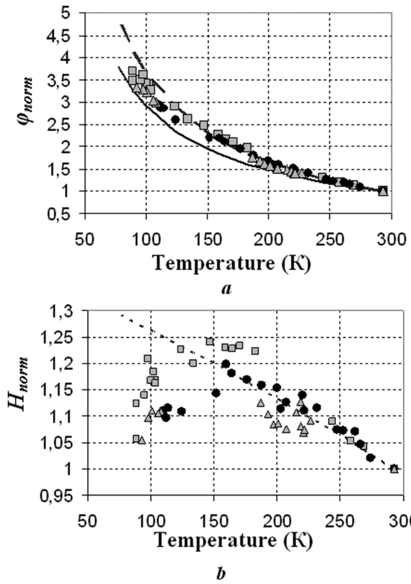

Fig. 4. Theoretical (lines) and experimental (dots) dependences of (a) normalized angle of rotation of the polarization plane and (b) normalized strength of the magnetic field on temperature for Nd-Fe-B magnets.

B. Increasing the Magnetic Field

In addition to the increasing Verdet constant, there is one more effect occurring in the cryogenic FI—an increase in the field of permanent magnets under cooling conditions. According to (1), both effects lead to an increase in the rotation angle of the polarization plane φ. Fig. 4(a) presents the results of measurement of the temperature dependence $\varphi_{\mathrm{norm}} = \varphi/\varphi_0$, where φ_0 is the value of the rotation angle of the polarization plane at room temperature 293 K. The solid line shows the dependence representing the change of the Verdet constant by (5); the dashed line is a calculated in the trend of [17], taking into account the increase of both the Verdet constant and the magnetic field of permanent magnets. Dependences of the normalized magnetic field strength $H_{\mathrm{norm}} = H/H_0$ (where H_0 is the value of angle of rotation of the polarization plane at room temperature 293 K) on temperature are presented in Fig. 4(b). Different types of points indicate experimental realizations with different cooling speeds. In the slowest (circles) realization, the magnetic field of the magnets was smoothly increased up to 160 K, i.e., in more than half of the temperature range. The plots show that, at the reached temperature of 89 K, the rotation angle of the polarization plane increased by a factor of 3.7, compared with its value at room temperature, and amounted to 36.1°.

Note that our experiments were performed not with a single ferromagnetic ring, as in [17], but rather with a magnet system with traditional Nd-Fe-B magnets used in room-temperature

Faraday rotators. The magnet system is comprised of six rings. Each ring experiences both the demagnetizing action of neighbor rings and mechanical action from the metal casing of the cell. However, we encountered the same difficulty as in [17]—the change in properties of the magnetic alloy which can be classified as phase transition.

What characterizes the phase transition? One of the most important properties of magnets is magnetic anisotropy (inequality of magnetization energy along different directions in the crystal) [18] related to relativistic interactions between atoms of the crystal. The magneto-anisotropic properties of crystals are characterized by magnetic anisotropy constant K_1 [18]. In magnetic alloys with rare-earth metals, an abnormally high magnetic anisotropy can be achieved [19] and thus a high value of coercitive force. This is why we used sintered polycrystalline grain-oriented magnets from Nd-Fe-B alloy with tetragonal crystal lattice. In such magnets at $T > 135$ K, the constant $K_1 > 0$ and the axis of easy magnetization coincides with the symmetry axis of the Nd-Fe-B crystal lattice [19]. With further cooling, K_1 changes its sign, and the easy magnetization axis is degenerated into a conical surface around the symmetry axis of the crystal lattice [18]. Therefore, there is a parameter that describes the symmetry of the polycrystalline system under consideration, which is zero at $T > 135$ K and gradually grows at cooling. This parameter is an angle between the easy magnetization axis and the symmetry axis of the crystal lattice, and the process characterized by this parameter is the second-order phase transition [20].

We also performed experiments with magnets from samarium-cobalt alloy (Sm-Co). These magnets are weaker than Nd-Fe-B (i.e., they have a lower product of coercitivity force and residual magnetization of material), but the magnetic anisotropy constant of such an alloy K_1 remains positive over the whole range of temperatures we considered. This means, in turn, that the symmetry axis of the crystal lattice of the alloy and the easy magnetization axis coincide, and no phase transition occurs.

In our experiment, we used MOC-10 glass [1] as the magneto-optical element (analog: glass M-24, Kigre, USA) with a length of 14 mm and a diameter of 6 mm. The initial angle of rotation of the polarization plane (at room temperature) was 6°, and at the reached temperature of $\sim 100\,\mathrm{K} - 21.4^{\circ}$. Fig. 5 shows one of the experimental realizations recorded during half a day. It is evident that, in contrast to Nd-Fe-B magnets, experimental points have no random spread and well agree with theoretical calculations over the whole temperature range of interest. This confirms the fact that there is no phase transition in this temperature range and shows the perspective of using Sm-Co magnets in cryogenic FIs.

IV. Increasing the Magnetic Field of Permanent Magnet Systems

In Section II, the magnetic field was increased by use of superconducting solenoids cooled to helium temperatures. As been mentioned above, such solenoids can generate on their axis uniform magnetic fields up to 100 kOe, while in traditional permanent-magnet Faraday rotators the field value is much

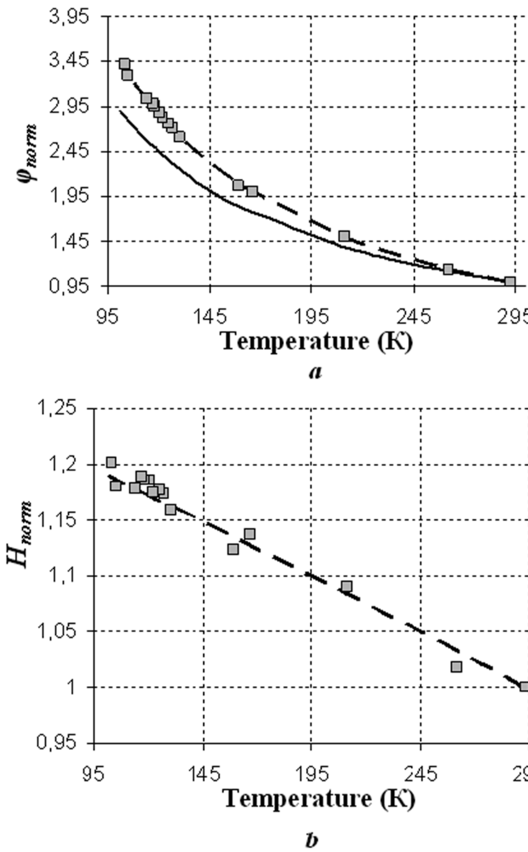

Fig. 5. Theoretical (lines) and experimental (points) dependences of (a) normalized angle of rotation of polarization plane and (b) normalized strength of magnetic field on temperature for Sm–Co magnets.

lower $(< 20\,\mathrm{kOe})$. To the best of our knowledge, a record value of the magnetic field in permanent magnet system is 50 kOe achieved in the channel with a diameter of only 0.15 mm. However, the undeniable advantages of traditional Faraday rotators such as compactness, simplicity of operation, and absence of expensive cryogenic equipment will always be an important argument for choosing between magnet systems (MS), and the problem of increasing the field through optimal arrangement of permanent magnets will remain important.

It should be noted that increasing the magnetic field of the permanent MS is not simple for two reasons. First, an increase in H suggests that the magneto-optical element should be shortened, thus imposing additional requirements on the transverse magnetic field uniformity. Second, an increase in H requires magnet mass build-up, which intensifies the demagnetizing action of neighbor magnets. Moreover, to achieve a required distribution of the magnetization vector in the MS of the Faraday rotator, one has to overcome technological difficulties both on the stage of creation of elements and further when assembling the MS. Our MSs are a set of axially and radially magnetized rings. We developed software with which we can calculate MSs composed of any arbitrary number of rings and predict the magnetic field value to no worse than 1% accuracy. In addition, the software can solve problems of optimization of various MS parameters (e.g., external dimensions of the MS and lengths of the magneto-optical element). As a result, our method allows creation of MSs with an isolation ratio of more than 40 dB.

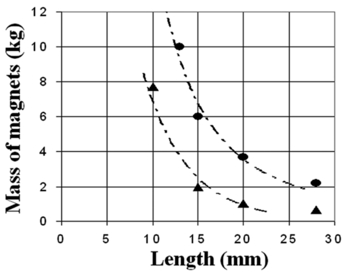

Fig. 6. Mass of the MS (Nd-Fe-B) versus length of magneto-optical TGG crystal with diameter of 10 (triangles) and 20 mm (circles).

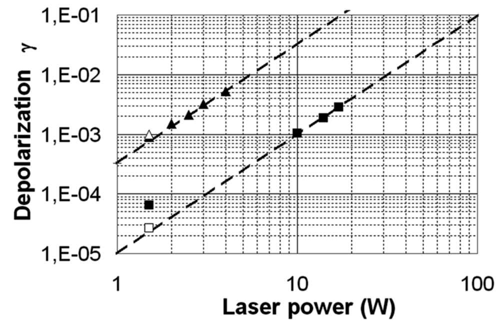

Fig. 7. Thermally induced depolarization versus power in a glass disc with cooling through end face by means of a sapphire window (squares) and without window (triangles); at room temperature (solid points) and at 89 K (open points).

Fig. 6 shows dependences of masses of the FR magnets produced by our MS assembly method on the length of TGG crystal magneto-optical element for two clear apertures of 10 and 20 mm. It is seen that there are some optimal sizes of the MS. If these sizes are exceeded, it becomes ineffective to reduce the length of the element L because the magnetic field grows insignificantly. The maximum strength of the magnetic field that we have achieved is 17 kOe [11]. Now we are developing a new algorithm of creating MSs in which the field strength would reach 30 kOe. This will help eliminate the existing limitation on shortening the magneto-optical elements.

V. Discussion

In this study, we have experimentally studied several original Faraday rotator designs with short magneto-optical elements. The magneto-optical elements were shortened either by increasing the magnetic field or due to growth of the Verdet constant under cooling conditions. In turn, the magnetic field was increased either by cooling the permanent magnets, by optimally arranging the MS, or by using superconducting solenoids. As a result, we have created FMs based on 9-mm-long glass MOC-04 and 3.5-mm-long TGG crystal, and a cryogenic FI on 3.2-mm-long TGG crystal with an isolation ratio of 32, 23, and 41 dB, respectively, at laser powers up to 100 W.

Let us estimate maximum average power $P_{\max}$ at which the cryogenic Faraday isolator can operate. According to [17], for a given γ, we have

$$P_{\max} \propto \frac{\kappa}{L\alpha Q} \tag{6}$$

where α and κ are coefficients of absorption and thermal conductivity, and Q is the thermo-optical constant [2].

Experiments have shown that transition from room temperature to 77 K permits a five-time reduction of the crystal length L, and the product αQ is decreased three times at 77 K [11], i.e., maximum average power $P_{\max}$ is increased by a factor of 15. In flux-grown TGG crystals, cooling to 77 K twice increases the thermal conductivity [21], thus increasing the maximum average power by a factor of 30 (instead of 15). Thus, we believe that the described cryogenic FI will provide sufficient isolation (30 dB according to Fig. 3) at $P_{\max} = 3$ kW. The use of superconducting solenoids instead of permanent magnets in the MS, as described in Section II, will enable an increase of $P_{\max}$ by a factor of 75 up to $\sim$ 7-8 kW.

Due to cooling, the magneto-optical element may be made shorter so that disc geometry rather than rods can be used (see Sections II–A and Section III). In this case, it is advisable to cool the magneto-optical element through optical surfaces, e.g., by means of a metal disc (see Section II–A) or glued sapphire windows that have an extremely high thermal conductivity (30 W/K $\cdot$ m at room temperature and 1000 W/K $\cdot$ m at 77 K [22]).

We conducted experiments with an absorbing 1-mm-thick glass disc both with heat removal through a single sapphire window and without this window. In a first experiment, power dependences of depolarization were measured. The results presented in Fig. 7 (solid points) show that, at an aspect ratio of 0.6, the presence of the sapphire window decreases by a factor of ~ 14 the thermally induced depolarization occurring in the sample. In a second experiment, a disc with a glued sapphire window and without any window was cooled to nitrogen temperatures. The results presented in Fig. 7 (open points) show that cooling to nitrogen temperatures of the sample without the sapphire window has no noticeable effect, but cooling with the sapphire window leads to a more than twofold decrease of depolarization. The results of these experiments, provided the aspect ratio is kept unchanged, suggest a more than 400-fold increase of the maximum average power instead of the 75-fold increase, i.e., $P_{\max} \sim 50$ kW.

Another approach to decreasing the thermally induced depolarization in magneto-optical elements of FIs and FMs is to use new magneto-optical media with lower absorption and higher thermal conductivity. Unfortunately, the Verdet constant is typically low in such media. Examples of such media include YAG crystals and gadolinium gallium garnet (GGG) crystals. The Verdet constant of GGG crystal is almost six times lower than in TGG $-$ 0.37 deg/kOe $\cdot$ cm [23]; however, the thermal conductivity coefficient in GGG (9 W/K $\cdot$ m [21]) is twice as high as in TGG (4.5 W/K$\cdot$m [21]). In addition, when GGG crystal is cooled from 300 to 70 K, the thermal conductivity coefficient of the crystal increases by a factor of 6.7 [21]. Since GGG crystal is a paramagnet [24], its Verdet constant changes in inverse proportion to temperature (6). Thus, according to (1), (4), and (5), cooling of the GGG magneto-optical element to 70 K will provide a 2.3-fold increase in power of passing radiation with the isolation ratio remaining unchanged.

The Nd:YAG crystal is a well-studied medium which is being widely employed as an active element of solid-state lasers. Earlier, the use of this crystal as a magneto-optical element was mainly avoided because of its low Verdet constant. The thermal conductivity coefficient of this crystal is 10 W/K $\cdot$ m at room temperature and is ten times greater at 70 K [21]. Bearing in mind that Nd:YAG is also a paramagnet [25], one may expect a fourfold increase in laser power at nitrogen temperatures. We studied the possibility of creating a Faraday rotator based on superconducting solenoids with the Nd:YAG crystal with an Nd ion concentration of 1 at.%, diameter of 13 mm, and length of 113 mm. A 45° angle of rotation of the polarization plane of passing radiation was achieved at the field value of 44 kOe. The calculated value of the Verdet constant of Nd:YAG crystal was 0.0904 deg/kOe $\cdot$ cm (for $\gamma = 1076$ nm), which is in agreement with the 0.088–0.12 deg/kOe $\cdot$ cm value obtained earlier for a wavelength of 1064 nm [23]. However, poor quality of the crystal we used did not allow us to obtain an acceptable value of isolation, which was as low as 20 dB.

Currently, there are FIs that reliably operate at subkilowatt average powers and are suited for $P_{\max} = 2\text{-}3$ kW [11], [12]. These FIs are designed with compensation of thermally induced depolarization [2] and operate at room temperature with traditional permanent magnets. For example, according to this design, we created a wide-aperture FI with two TGG crystals with a diameter of 20 mm and a total length of 28 mm [11]. As we managed to successfully solve the problem of further increase of the magnetic field, the total length of the crystal was shortened to 18 mm [12]. If, in such an FI, the magneto-active element is cooled to nitrogen temperatures, then, according to [17], a 1.9-fold decrease in optical anisotropy parameter ξ will provide an additional nearly 1.65-fold increase in maximum power $P_{\max}$. Thus, if we take into account all of the abovementioned effects, we may expect a more than 600-fold increase in maximum power $P_{\max} = 2\text{-}3$ kW, i.e., $P_{\max} \sim 1$ MW.

VI. Conclusion

We have experimentally studied several original Faraday rotator designs with short magneto-optical elements. The results will help create an FI that would provide reliable isolation of laser radiation with power up to 50 kW or even up to 1 MW if we additionally use the effect of depolarization compensation.

We have considered and confirmed the principle possibility to employ, along with widely used magneto-active glasses and TGG crystals, nontraditional magneto-active media with high thermal conductivity such as YAG and GGG crystals. We have developed software to calculate simple-in-assembly and compact MSs that generate fields with any predetermined uniformity. This software also makes it possible to optimize parameters of the MS with the aim to use short magneto-optical elements.

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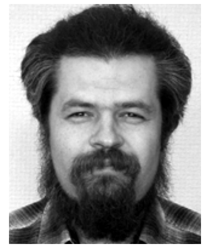

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