Permanent-magnet Faraday isolator with the field intensity of more than 3 Tesla

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A permanent-magnet system with maximum magnetic field exceeding 3 T, which is a record value for Faraday isolators, has been created. The magnitude of the field in the system is close to the theoretical limit that can be achieved at optimal magnetization distribution. This is possible thanks to the use in the central area of the system of magnetic conductors that possess a saturation induction higher than the residual induction of the strongest magnets and provide more optimal magnetization distribution than magnets. But the main feature of the system is control of demagnetizing fields in the center of the system by optimizing the position and shape of magnetic conductors, thus retaining the maximum volume of the magnets in the core of the system without the risk of their magnetization reversal. The technology of controlling demagnetizing fields by means of magnetic conductors was first proven. The created system is promising for the development of Faraday isolators for high-power lasers, as it allows decreasing the length of magneto-optical element and reducing parasitic heat generation. Record results on maximum permissible operating power of Faraday isolators based on CeF_3 and TSAG crystals was obtained with the use of this system. It is also promising for the development of Faraday isolators for "eye-safe" and mid-infrared radiation, since the Verdet constant of magneto-active crystals in these wavelength ranges reduces substantially compared to the near-infrared and the creation of strong magnetic field becomes of principal importance for providing a needed angle of Faraday rotation.

One of the key elements of lasers is a polarization optical isolator based on the Faraday effect – the Faraday isolator. These devices protect sensitive laser elements from the reflected radiation and prevent the risk of self-excitation of amplification cascades, and they are handy tools for organizing multipass amplification schemes.

An important component of the Faraday isolator is its magnetic system. The magnetic field parameters directly affect the resulting characteristics of the device. By creating a required transverse profile of the magnetic field of the system, it is possible to improve the isolation due to compensation for the radiation polarization distortions caused by the temperature dependence of the Verdet constant[1] and magnetization of the magneto-optical element.[2] By creating a required longitudinal profile of the field, stable isolator operation with a change of the ambient temperature can be provided.[3] Controlling magnetic field inhomogeneity is of principle importance in the

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development of large-aperture Faraday isolators demanded for lasers with high average power.[4,5] High field inhomogeneity can also be used, for example, for laser beam apodization.[6]

However, the most important requirement to the magnetic field of Faraday isolators is its high intensity. Increasing field intensity allows using shorter magneto-optical element, thereby reducing heat generation and parasitic thermal effects which are the main limitation for using Faraday isolators in high-power lasers. Magnetic systems with high field intensity are also required for the development of Faraday isolators intended for lasers of the mid-IR range, as the Verdet constant of magneto-active media in this range is much lower than in the near-IR.[7]

The generation of strong fields in magnetic systems of Faraday isolators has been a challenging problem for quite a time that is being solved step by step. Progress in this field is stimulated by the appearance of new magnetic materials, as well as by upgrading the system design. The recent achievements in this area were the creation of a magnetic system with a field magnitude of 2.1 T in 2009[8] and with a field magnitude of 2.5 T in 2013.[9] Here, we report a system with a record high maximum magnetic field value over 3 T.

The magnetic systems for Faraday isolators are traditionally manufactured as a set of coaxially and radially magnetized rings. This construction has a number of fundamental drawbacks. First of all, such a magnetic system structure is characterized by a strongly nonoptimal magnetization distribution. Another significant shortcoming is high susceptibility to demagnetization of the central part of the construction, but this problem arises only in systems with high intensity of the magnetic field and was first taken into account in.[9]

The magnetization distribution in a Faraday isolator magnetic system is regarded to be optimal if its direction in the volume is changing continuously depending on the position of a given point relative to the magneto-optical element. As follows from fig. 1a, a small magnet volume with magnetization **M** and coordinate **r** produces at the coordinate origin a field having a projection on the Z-axis equal to

$$dB_z = \frac{M(r)d^3r}{r^3} \cdot \left[2\cos\theta\cos\psi + \sin\theta\sin\psi \right], \tag{1}$$

where θ is the polar coordinate of the magnet volume and Ψ is the angle between its radius-vector **r** and the magnetization vector.

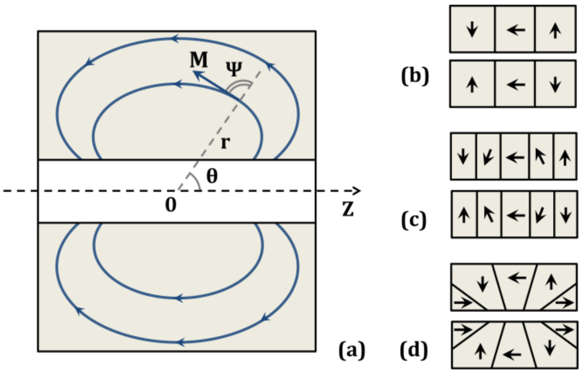

FIG.1. (a) Magnetic system with continuously varying magnetization vector and approximation of optimal magnetization distribution by discrete distributions: (b) traditional case with coaxially and radially magnetized rings, (c) approximation using rings with nonorthogonal direction of magnetization, (d) approximation by means of coaxially and radially magnetized cones.

As was noted in,[10] the condition of producing maximal field is fulfilled for a distribution corresponding to $2\mathrm{tg}\Psi = \mathrm{tg}\theta$. For such a magnetization distribution assuming that the magnetic system of a Faraday isolator is infinite along Z, an expression for the magnetic field value in the center was obtained in:[11]

$$B_z\left(0\right)=\int_0^1\sqrt{1+3x^2}\,dx\cdot B_r\ln\left(\frac{D}{d}\right)\approx 1.38\cdot B_r\ln\left(\frac{D}{d}\right) \tag{2}$$

where D is the external diameter of the magnetic system, d is its internal diameter, and $B_r = 4\pi M$ is the residual induction of the magnets.

Such formulas can be derived for other distributions too, including discrete ones.[11] Despite the used approximation of an infinitely long system, these formulas are of great practical importance. Firstly, they show the advantage of one magnetization distribution over another, and, secondly, they may be used for quite precise estimates of the fields in finite-length systems.[11]

The creation of magnetic systems with continuously changing magnetization direction is impracticable, but it is possible to come closer to solution of this challenge making use of different approaches. For example, a magnetic system, in which rings with nonorthogonal magnetization (Fig. 1(c)) were used besides coaxially and radially magnetized rings, was proposed and implemented in the work.[12] The construction comprised of axial and radial cone magnets was investigated in[11] (Fig. 1(d)).

The manufacture of magnetic systems using magnets other than coaxially and radially magnetized rings is a technically difficult task that is not always justified by gain in the field magnitude. However, there is still another way which may help approach closer to optimal magnetization distribution in a magnetic system of a Faraday isolator. It is application of soft magnetic materials (magnetic conductors), which is much easier technically.

The use of magnetic conductors in permanent magnet systems[10] was inspired by the fact that the saturation magnetization of some soft magnetic materials greatly exceeds residual induction of the strongest permanent magnets. System[10] was developed for X-ray dichroism experiment, but magnetic systems of Faraday isolators also have regions in which the magnetic field value is sufficient for the soft magnetic materials to reach saturation. Another advantage of using magnetic conductors in Faraday isolator magnetic systems is that they can be located in areas such that the magnetization induced in them should be directed more optimally than in radially or axially magnetized rings. The application of magnetic conductors in the Faraday isolator magnetic system was first reported in the work,[8] where the field of 2.1 T was reached in the center of the system.

A fundamentally important point in the development of magnetic systems with a strong magnetic field is the control of demagnetization. In an attempt to produce such fields, part of the magnets inevitably fall into regions of strong local demagnetizing fields. It is critical to prevent magnetization reversal even of the smallest part of magnets, otherwise the region with reversed magnetization will start to create in its neighborhood a field with the intensity opposite to the initial magnetization direction, as a result of which the strong demagnetizing field will move deep into the structure and it may commit self-magnetocide. The first efforts towards controlling this effect in a magnetic system of a Faraday isolator were made in the work.[9] The areas of magnets that could potentially get into the region with reversed magnetization during assembly were removed. The result of using this approach was a field of 2.5 T in the center of the system, but its shortcoming was that magnetic material was removed from the most important central part of the system.

The magnitude of the demagnetizing field can also be controlled by magnetic conductors by optimizing their shape and location. Manufacturing magnetic conductors of complex shape is technically easy as they are simple to process. This approach was implemented in the present work. As a result, the volume of the removed material was reduced significantly which enabled achieving fields exceeding 3 T in the central area of the system.

An easy to manufacture magnetic system consisting of magnets only with coaxial and radial magnetization directions was built. Its internal and external diameters are 14 mm and 130 mm, respectively, and length 130 mm, i.e. it has size similar to that of its predecessors.[9] Nevertheless, the field obtained in this system was the record one for the Faraday isolators. The schematic diagram of the system is shown in Fig. 2(a). The central coaxially magnetized ring is made of N38EH magnet, and the side radially and coaxially magnetized rings are made of N48M magnets. Magnetic conductors made of ARMCO steel are also used in the structure. One of them serves as an external screen and housing, and the other two placed in the central area of the system are field concentrators. The B-H curves of the used magnets and magnetic conductors are plotted in Fig. 2(b). One can see that the saturation induction of the magnetic conductors is much higher that the residual induction of the magnets, hence, in the saturation regime they produce a stronger magnetic field around themselves than magnets.

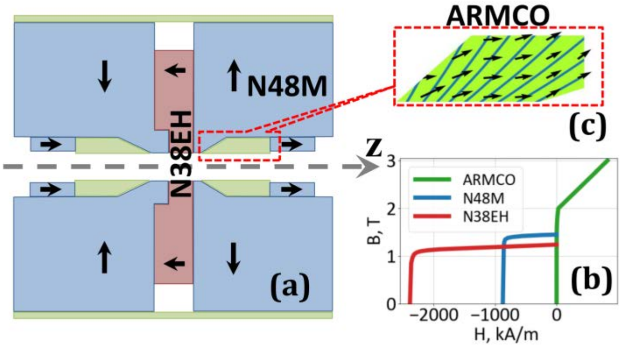

FIG.2. (a) Section view of magnetic system, (b) B-H curves of magnetic materials used in the system, (c) magnetization vector distribution in internal magnetic conductor. The lines show optimal distribution.

However, to obtain gain from the use of internal magnetic conductors, their magnetization saturation is not enough, appropriate direction of the magnetization is required as well. The magnetization vector distribution in one of the magnetic conductors is shown in Fig. 2(c) in comparison with optimal distribution. Clearly, with a proper choice of the shape and position of a magnetic conductor, magnetization is induced in it with a distribution more optimal than can be created using coaxially and radially magnetized magnets.

The magnetization distribution in a magnetic conductor is not the only criterion of optimizing its shape and position. An important factor for obtaining strong fields is also controlling system demagnetization, for which magnetic conductors may be used as an instrument. The system was designed so as to minimize the volume of removed magnets falling into the region with reversed magnetization. The region of location of magnetic conductors was optimized with allowance for this criterion. As a result, as compared to the previous system with a lower field value,[9] the magnetic conductors in the considered system were drawn aside from the magneto-optical element area and the volume of magnets that could undergo the magnetization reversal became insignificant.

The calculations of the magnetic field during optimization of the system parameters were made using the ELCUT software package.[13]

The designed magnetic system was implemented and investigated in experiment. The results of magnetic field measurements in the central area of the system are shown in the graph in Fig. 3 together with the result of the calculation.

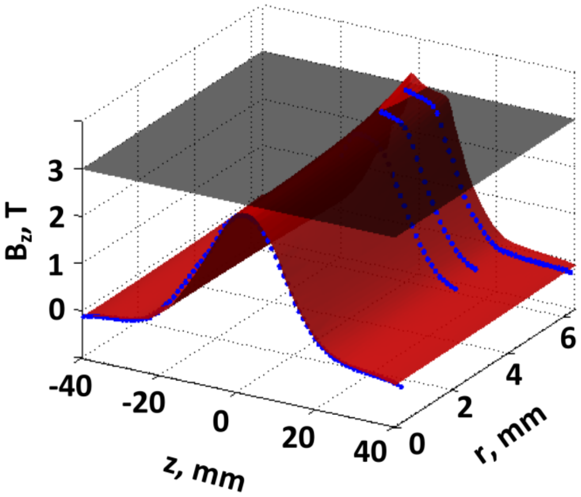

FIG.3. Calculation of the magnetic field strength in the central area of the magnetic system (red surface) and its experimental measurements (dots). z is the longitudinal coordinate and r is the transversal coordinate. Dark grey plane shows 3 T level.

It can be seen from the figure that, in a definite area, the magnitude of the field is higher than 3 T and the measurement data agree well with the calculations in the entire region under study.

It is interesting to compare the obtained magnetic field value with the theoretically predicted admissible limit according to formula (2). For this the correction introduced by finiteness of the system length should be taken into account. In our case, according to,[11] for the system length equal to the external diameter this correction to the field is -0.29*B_r. By substituting the external-to-internal diameter ratio and the residual magnet induction averaged over the volume that is approximately 1.3 T, we obtain the field value equal to ~3.6 T. This means that in the created system the magnitude of the obtained field is quite close to the maximum permissible theoretical value (> 80%). It should be understood that formula (2) does not take into consideration the demagnetization effect which is of fundamental importance. Thus, further significant advancement to the range of stronger magnetic fields due to structural improvements of the systems should not be expected.

The developed magnetic system has already been used for the creation of unique Faraday isolators. In particular, it was used in the isolator with a traditional scheme based on a CeF_3 crystal.[14] Due to the large magnetic field value, the crystal length needed to provide a rotation angle of 45 degrees was only 8 mm. The magnitude of thermally induced depolarization arising in a crystal of such length ensured an isolation ratio of the device of 30 dB at a laser power up to 700 W. It is plotted *versus* radiation power in Fig. 4.

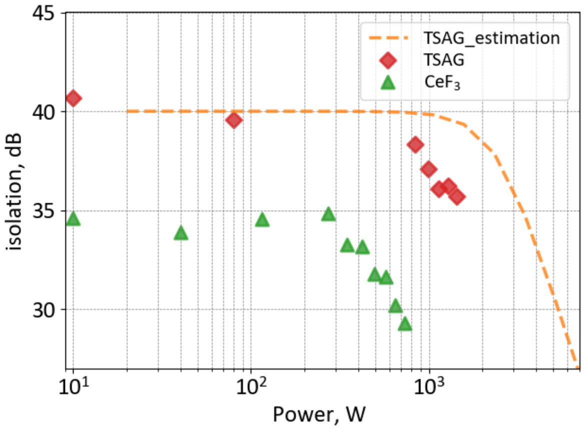

FIG.4. Isolation ratio *versus l*aser radiation power in Faraday isolators based on the developed system and CeF$_3$ [14] and TSAG [16] crystals

The CeF$_3$ crystal has magneto-optical and thermo-optical characteristics similar to the TGG crystal.[15] The best isolator on a single TGG crystal in a magnetic system with a field of 2.5 T had the isolation ratio of 30 dB at a power approximately 600 W.[9]

This magnetic system was also used in the Faraday isolator based on TSAG crystals with thermally induced depolarization compensation and without reciprocal rotator.[16] An isolation ratio of 35.7 dB at a power of 1.44 kW was attained. The system allowed an almost two-fold shortening of magnetic elements, which could provide an isolation ratio of 30 dB at the operating power of 5.5 kW (Fig. 4).

The created system is very promising for high-power isolators with compensation of thermally induced depolarization without reciprocal rotator, as in this case, in contrast to the scheme with rotator, the region with strongest magnetic field is occupied by magneto-optical elements ensuring their minimal length. Such isolators may be advanced further thanks to the recent discovery of magnetically active crystals with a negative optical anisotropy parameter such as NTF,[17] KTF[18] and terbium containing cubic zirconia[19] promising for this scheme.

The considered system can also be used for the development of high-power isolators based on media with a high value of the Verdet constant, for example, a Tb$_2$O$_3$ crystal, since this combination gives an important additional advantage. Such a magneto-optical element in this magnetic system will be disc-shaped. In this case, the end heat sink will play a significant role, which will change the direction of the temperature gradient. The direction of the axes of thermally induced depolarization caused by the photoelastic effect will acquire an axial component, as a result of which the radial component will be decreased and the magnitude of thermally induced depolarization will be reduced.

Another prospective application of the system in Faraday isolators is for the “eye-safe” and mid-IR radiation, as the Verdet constant of magneto-active crystals in these wavelength ranges is much smaller compared to the near-IR and producing a strong magnetic field becomes of fundamental importance for ensuring the required angle of

Faraday rotation. For example, for the EuF_2 crystal that has prospects for the future,[7] the length of a magneto-optical element in the developed magnetic system shall be quite accessible 18 mm for the radiation wavelength of 1550 nm.

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