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Wide-aperture Faraday isolator for kilowatt average radiation powers

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Abstract. **A Faraday isolator with an aperture of 20 mm and compensation of thermally induced polarisation and phase distortions of laser radiation is fabricated and tested experimentally. A considerable improvement in the isolation degree over a traditional Faraday isolator is demonstrated. For radiation power up to 750 W, the isolation degree lies in the range 24 – 26 dB and is limited only by the quality of TGG crystals.**

Keywords: *Faraday isolator, isolation degree, depolarisation compensation, thermally induced birefringence, thermal lens.*

1. Introduction

The principal problem restricting the use of Faraday isolators (FIs) in high-power lasers is the inevitable heat release in the magnetically active elements. The inhomogeneous temperature distribution over the sample volume leads to phase distortions (thermal lens), the nonuniform distribution of the angle of optical rotation caused by the temperature dependence of the Verdet constant, mechanical stresses and the linear birefringence associated with it (photoelastic effect).

The thermal lens does not affect the isolation degree of the FI, but leads to strong phase distortions of radiation. Such distortions can be compensated by using a misaligned telescope [1] or an absorbing medium with a thermal lens opposite in sign to the thermal lens of the magnetically active medium [2 – 4]. It was shown in [5] that for a 150-W Gaussian beam in the absence of compensation of distortions, more than 95 % of power is transformed by a thermal lens into higher transverse modes, whereas no more than 5 % of power is transformed if a DKDP crystal with a negative thermal lens is used for compensation of distortions.

The isolation degree is determined by polarisation distortions caused by the photoelastic effect, while the contribution from the temperature dependence of the Verdet constant is negligible [6, 7]. This imposes a restriction on the avearge power of radiation passing through the FI for a given isolation degree. To compensate for such polarisation distortions, new FI schemes were proposed in [6] which can provide theoretically a high isolation degree for kilowatt average powers. The efficient operation of such FIs was experimentally demonstrated for radiation powers less than 100 W [8]. The results presented in [9] for kilowatt powers were much worse than the theoretical predictions [6].

In this paper, we demonstrate experimentally a considerable decrease in phase and polarisation distortions in an FI for radiation power up to 750 W. The obtained results are compared with the theoretical predictions. The possibility of using such FIs for kilowatt powers is discussed.

2. Faraday isolator with compensation of polarisation distortions

Consider the operation of a conventional FI scheme (Fig. 1a) and a new scheme (Fig. 1b) with depolarisation compensation. The compensation involves the replacement of one magnetooptical element rotating polarisation by 45° with two elements, each of which rotates polarisation by 22.5°. A reciprocal polarisation rotator turning the polarisation by 67.5° is installed between these two elements. In this case, the distortions produced in the first magnetooptical element are partially compensated after passage of radiation through the second element.

In an ideal FI, the radiation is totally reflected by

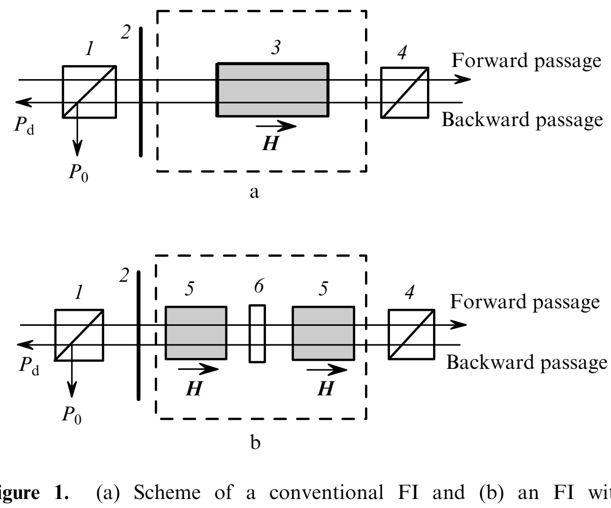

Figure 1. (a) Scheme of a conventional FI and (b) an FI with depolarisation compensation [6]: (*1*, *4*) polarisers; (*2*) half-wave plate; (*3*) 45°-magnetooptical element; (5) 22.5°-magnetooptical element; (6) 67.5°-reciprocal optical rotator. The dashed rectangles contain the magnetic system of the FI.

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polariser (*1*) during its return trip. However, magnetic field nonuniformity, flaws in the optical quality of the elements, and the thermal effects (upon an increase in laser power) lead to polarisation distortions. As a result, the main part of the radiation power P_0 is reflected from polariser (*1*), while the depolarised component of power P_d passes through it. The quantity

$$\gamma = \frac{P_d}{P_d + P_0} \tag{1}$$

is called the depolarisation or polarisation decoupling of the FI, while its isolation degree I (measured in decibels) is defined by the relation

$$I = -10\lg\gamma. \tag{2}$$

Using the results presented in [6], we designed and fabricated a FI with depolarisation compensation for high-power laser radiation at a wavelength of 1.07 μm. The FI is a magnetic system (dashed rectangle in Fig. 1b) consisting of a set of Nd–Fe–B magnetic rings containing two terbium–gallium garnet (TGG) crystals and a quartz crystal between them to serve as a reciprocal optical rotator. The magnetic system fabricated in this way produces a highly uniform magnetic field up to 12 kOe over the aperture of the crystals. Figure 2 shows the distribution of the magnetic field along the radiation propagation axis.

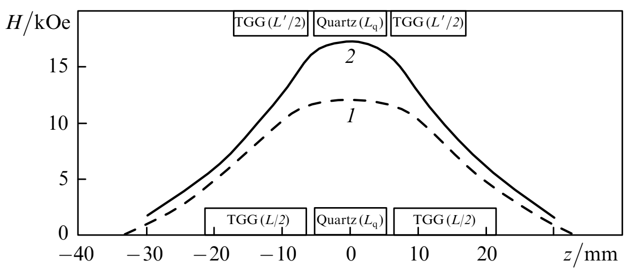

Figure 2. Distribution of the magnetic field strength H along the z axis of the magnetic system for the FI under consideration (*1*) and an FI with an enhanced magnetic field (*2*). For the sake of clarity, the size and position (along the abscissa axis) of crystals are shown in rectangles for the FI under consideration (below) and the FI with an enhanced magnetic field (above). The size of the rectangles along the ordinate axis is immaterial.

For low-power radiation (of a few watt), the isolation degree is limited only by imperfections of the crystals and magnetic field inhomogeneity, and may be much larger than 30 dB. With increasing power, the isolation degree decreases due to thermal effects in TGG crystals. We used TGG crystals with [001] orientation (the radiation wave vector is directed along one of the crystallographic axes). In the new layout shown in Fig. 1b, the necessary condition for minimum depolarisation is that the orientation of all the crystallographic axes should be the same in both TGG crystals. The radiation polarisation is not important in this case. For the conventional layout of an FI, thermally induced depolarisation depends on the angle between the direction of radiation polarisation and one of the crystallographic axes perpendicular to the wave vector [6]. The necessary condition for minimising depolarisation is that one of the crystallographic axes of the TGG crystal must form an angle of 45° with the bisector of the angle between the directions of radiation polarisation at the input and output of the FI. For an optimal alignment of the FI, the depolarisation without compensation (γ_0) (Fig. 1a) and with compensation (γ_r) (Fig. 1b) are determined by expressions [6]

$$\gamma_0 = A_0 p^2, \tag{3}$$

$$\gamma_r = A_r\left(1 + \frac{2}{3}\xi^2 + \xi^4\right)p^4, \tag{4}$$

where

$$p = \frac{Q\alpha L P_L}{\lambda\kappa}; \quad \xi = \frac{2p_{44}}{p_{11} - p_{12}}; \tag{5}$$

λ and P_L are the wavelength and power of laser radiation; L, α, κ, p_{ij}, and Q are the total length, absorption coefficient, thermal conductivity, photoelastic coefficients and thermooptical constant respectively [10] of the magnetically active medium. For Gaussian distribution of the beam, $A_0 = 14 \times 10^{-3}$ and $A_r = 4 \times 10^{-6}$. We used two TGG crystals ($\xi = 2.25$, $\alpha = 3 \times 10^{-3}$ cm^{-1}, $\kappa = 5$ W K^{-1} m^{-1}, $Q = -17 \times 10^{-7}$ K^{-1}) with a total length $L = 28$ mm.

3. Experimental results

To confirm the depolarisation compensation effect, we performed experiments with an FI assembled in a scheme with depolarisation compensation and without it. Figure 3 shows the measuring scheme. We used nonpolarised radiation of 1.07-μm cw YLS-750 SM fibre laser (*1*) (IRE–Polyus) with power P_L varying in the range 0–750 W. The transverse distribution of the beam intensity was nearly Gaussian. The beam is split by spar wedge (*3*) into two beams with equal powers and orthogonal polarisations. Because these beams have equal diameters of ~ 12 mm and the angle between them is less than 0.5°, their paths in TGG crystals were virtually the same. This allows us to use radiation with both polarisations for heating. After passage through the FI, one of the beams was deflected to absorber (*8*), while the other, which is used for depolarisation measurements, was directed on spar wedge (*4*) rotated through 22.5° relative to wedge (*3*). The radiation was split into depolarised (P_d) and polarised (P_0) components. From the measured values of P_d and P_0, we calculated the depolarisation γ as a function of the laser power P_L using expression (1). In the experiment with depolarisation compensation (Fig. 3a), the FI was tuned to the maximum compensation for 750 W power. In the other experiment without depolarisation compensation, quartz rotator (*7*) was removed from the FI and mounted behind it (Fig. 3b). The position of the TGG crystal was not changed. This made it possible to perform measurements without realignment of the spar wedges.

The thermal lens was compensated for by using 5.5-mm thick DKDP crystal (*2*) (see Fig. 3) [4, 5] with its optical axis inclined at an angle of ~ 30° to the crystal axis. The crystal produces a negative thermal lens but does not depolarise the radiation. According to the data presented in [5], the beam divergence at a power of ~ 1 kW should increase compared to the diffraction divergence by a factor of 4.5 if a DKDP crystal is used, and a factor of 20 if the crystal is not used.

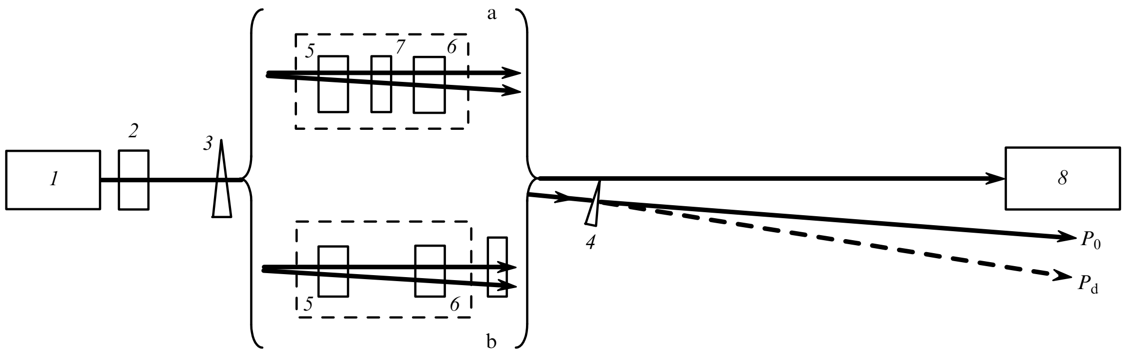

Figure 3. Experimental setup for measuring depolarisation in an FI with depolarisation compensation (a) and without it (b): (*1*) YLS-750 SM laser; (*2*) DKDP crystal; (*3*, *4*) spar wedges; (*5*, *6*) TGG crystals; (*7*) quartz crystal; (*8*) absorber. The dashed rectangles contain the magnetic system of the FI.

The results of measurement of depolarisation are presented in Fig. 4. For the FI without compensation of polarisation distortions and a beam power of less than 100 W, depolarisation is determined by the beam power as well as 'cold' depolarisation. For such a radiation power, the isolation degree is $\sim$ 30 dB, which meets the requirements for most applications. As the radiation power increases, depolarisation increases quadratically in accordance with (3) [curve (*1*)], and amounts to 4.5×10^{-2} for a power of 750 W.

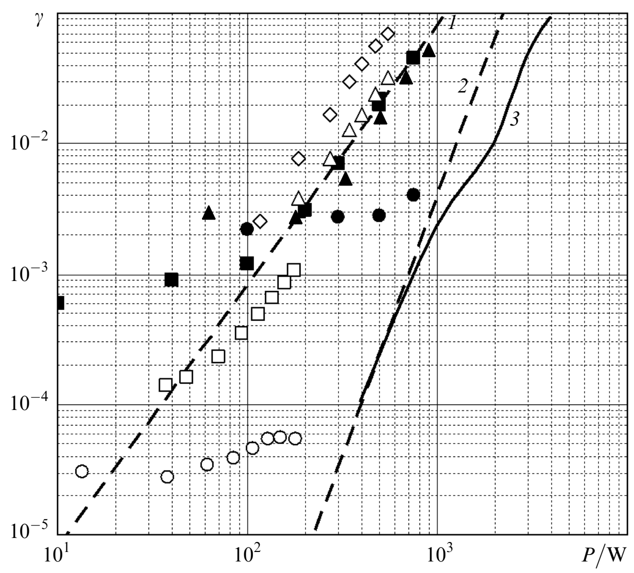

Figure 4. Dependence of depolarisation γ on radiation power P in an FI without depolarisation compensation [■, curve (*1*)] and with compensation [●, curves (*2*, *3*)] in commercial FIs manufactured by Litton (◇) [9], Linos (△) [9], EOT (▲) [9], as well as in an FI with an enhanced magnetic field with depolarisation compensation (○) and without it (□) [4]. Curves (*1*) and (*2*) were plotted by expressions (3) and (4), respectively; curve (*3*) corresponds to numerical calculations.

Let us compare the FI without depolarisation compensation described above with the commercial models of various manufacturers. The results of measurements for these models were borrowed from [9]. One can see from Fig. 4 that the isolation degree of our FI is not inferior to those produced by other manufacturers. Note that the crystals in our FI are not located at the maximum of the magnetic field since this site is reserved for a quartz rotator, which is not used in this scheme (see Fig. 2). By moving the crystals to the magnetic field maximum, we can reduce their length from 28 to 20 mm. According to Eqns (3) and (5), this reduces the depolarisation by 50 %.

In the case of compensation of polarisation distortions (dark circles in Fig. 4), the depolarisation is determined entirely by the quality of TGG crystals in the power range 0 – 500 W. Polarisation distortions are compensated efficiently, and an increase in depolarisation is observed only in the interval 500 – 750 W. For a radiation power of 750 W, the value of γ was found to decrease by a factor of 11 and the isolation degree was 24 dB. Formula (4) was obtained under the condition $p \ll 1$. However, strictly speaking, this condition does not hold for kW radiation powers, and the value of γ_r is determined by numerical calculations whose results are presented in Fig. 4 [curve (*3*)]. One can see that such an FI can ensure an isolation degree of 20 dB for radiation of 2 kW power.

4. Discussion

For a radiation power of 1 kW, about 8 W of thermal power is released in TGG crystals. Such a heat release may lead not only to a considerable temperature gradient, but also to an increase in the total average temperature of the crystals and hence to a variation in the angle of optical rotation [11]. For a 30 °C increase in the TGG temperature, the angle of optical rotation decreases by 4.5° resulting in a decrease in the isolation degree to 22 dB. To avoid this, a reliable heat removal from the crystals should be provided. In experiments involving depolarisation compensation over a period of 20 min for a power of 750 W, no appreciable increase in polarisation was observed. This indicates a quite efficient heat removal from the crystals.

The isolation degree of our FI is 24 dB for a radiation power of 750 W and is limited by the quality of the crystals. Our experiments show that the FI with depolarisation compensation can be used at radiation powers up to 2 kW. The radiation power can be increased further by modifying the FI. We have designed and developed a new magnetic system in which an increase in the magnetic field leads to a decrease in the overall length of the crystals from $L = 28$ mm to $L' = 18$ mm (Fig. 2) for a fixed aperture of 20 mm. Note that an increase in the magnetic field strength H is a complex problem for two reasons. First, an increase in H means a decrease in the length of the magnetooptical element, which imposes additional requirements on the transverse homogeneity of the magnetic field. Second, this increase leads to an increase in the mass of the magnets, which entails an increase in mutual demagnetising effect of adjacent magnets.

Coercive magnets, whose residual magnetisation can withstand stronger magnetic fields, are used in the modified FI. This makes it possible to increase the magnetic field inside the FI by varying the design of the magnetic system and doubling the mass of the magnets. Depolarisation in the FI upon an increase in magnetic field was measured for a radiation power up to 180 W [4]. It can be seen from Fig. 4 that depolarisation in our FI is much weaker than in all other FIs, with or without depolarisation compensation. Theoretical estimates show that this FI can be used for radiation power right up to 3 kW.

Further increase in the maximum admissible power for FI with depolarisation compensation can be attained by reducing the diameter of crystals while preserving the size of the FI. Calculations show that the total length L of the crystals can be decreased from 18 to 12 mm upon a decrease in the aperture from 20 to 10 mm. The value of L can be decreased further by replacing the 67.5° quartz rotator with two equivalent half-wave plates whose axes form an angle of 67.5°/2. Since the length of the quartz crystal $L_q = 10.7$ mm and the half-wave plate is shorter than 1 mm, such a substitution allows a decrease in the separation between TGG crystals by ~ 8 mm. In this case, the TGG crystals are subjected to a stronger magnetic field (Fig. 2) so that their length can be decreased to 10–11 mm. In accordance with Eqns (4) and (5), a decrease in L from 18 to 11 mm leads to an increase in limiting power from 3 to 5 kW.

Another way of increasing the power is by lowering the absorption coefficient α in the crystals. By replacing the TGG crystals having $\alpha = 3 \times 10^{-3}$ cm^{-1} in our experiments with TGG crystals having $\alpha = 1.5 \times 10^{-3}$ cm^{-1} [12], we were able to increase the limiting power to ~ 10 kW.

Note that a decrease in the length and absorption of magnetically active elements leads to an identical decrease in the polarisation and phase distortions. Therefore, the FIs proposed in this work can be used for effective decoupling radiation of power up to 10 kW, preserving its optical quality.

5. Conclusions

For a radiation power of 750 W, the polarisation distortions have been reduced by a factor of 11 in an FI (having an aperture of 20 mm) with compensation of thermally induced polarisation and phase distortions of laser radiation. The isolation degree is 24 dB and is limited only by the quality of the TGG crystals. According to theoretical estimates, such an FI can ensure a reliable isolation of radiation of up to 2 kW power. Faraday isolators for radiation powers up to 10 kW can be fabricated by modifying the magnetic system, decreasing the working aperture of the FI to 10 mm, and using TGG crystals with a smaller absorption coefficient.

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