Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Faraday isolator for high-power nonpolarized radiation

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ARTICLE INFO

Article history:
Received 18 April 2015
Received in revised form
14 May 2015
Accepted 18 May 2015

Keywords:
Faraday isolators
Magneto-optic systems
Thermal effects
Nonpolarized radiation
Thermally induced depolarization

ABSTRACT

We propose a Faraday isolator scheme in which high-power nonpolarized radiation is divided into two orthogonally polarized beams that pass through one MOE. The experimentally confirmed advantage of the scheme is reduction of thermally induced depolarization due to mutual thermal action of the beams optimally spaced apart. The advantage in the level of thermally induced depolarization over conventional schemes is up to 60%.

1. Introduction

With the advance of laser technology the average power of continuous and pulse-periodic radiation is constantly increasing. Therefore, reduction of thermal effects arising in different optical elements as a result of laser radiation absorption is becoming an urgent task. Optical devices based on the effect of nonreciprocal rotation of polarization plane, such as Faraday rotators and isolators are widely employed in laser engineering for isolation of optical radiation, organization of multipass schemes of laser amplifiers, compensation of thermally induced birefringence in active lasers elements, and so on. The key component of such devices is a magneto-optical element placed in a constant magnetic field. Faraday isolators (FI) are subject to strong thermal effects caused by radiation absorption ($\sim 10^{-3}\,\mathrm{cm}^{-1}$) in their magnetooptical elements (MOE). The heat absorption in the MOEs of Faraday isolators gives rise to birefringence due to the photoelastic effect and the related depolarized radiation component, which in turn reduces the isolation ratio of the device.

There are several approaches to decrease the thermally induced distortions in FIs [1]. First of them is improving of magnetic systems of FIs. Magnetic field increasing allows to reduce the length of magnetooptical element (MOE) and accordingly reduce all thermal effects. Other way is compensation of thermally induced birefringence [2,3]. The idea is similar to the method for compensation of thermally induced distortions in active elements of lasers. It consists in replacing one 45° Faraday rotator by two identical 22.5° rotators and a 67.5° reciprocal polarization rotator placed between them. Selecting an optimal magneto-optical medium instead of popular TGG crystal can reduce the thermally induced effects. Nowadays media with high Verdet constant for high-power FI that can surpass TGG is a subject of high interest [4–7]. Another approach is to cool the FI to liquid nitrogen temperatures ($T < 120$ K) [8]. Thermo-optical characteristics of the medium improve on cooling, the Verdet constant of paramagnetic materials and thermal conductivity grow on cooling, thermal expansion decreases. These factors became the underlying reasons for creating a cryogenic FI, a device in which both the MOE and the magnetic system of FI are cooled down to the liquid nitrogen boiling temperature. All of these methods lead to availability of FI working with laser power exceeding 1.5–2 kW [1].

FI is especially necessary in lasers for technological applications. Lasers used for engraving, cutting, material processing are suffer from backscatter radiation, so installation of FI is practically mandatory. The classical FI scheme (Fig. 1a) works with polarized light, but many present day lasers and amplifiers have nonpolarized light at the output [9–11], and losing half of power at the FI input polarizer is unacceptable. In these cases a scheme of two independent FIs each operating with its own polarization is used (Fig. 1b) [12,13]. We have proposed and studied experimentally an alternative FI scheme where orthogonally polarized beams pass through one MOE at an optimal distance from each other (Fig. 1c), which permits reducing the thermally induced depolarization due to the mutual thermal action of the beams.

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http://dx.doi.org/10.1016/j.optcom.2015.05.038
0030-4018/© 2015 Published by Elsevier B.V.

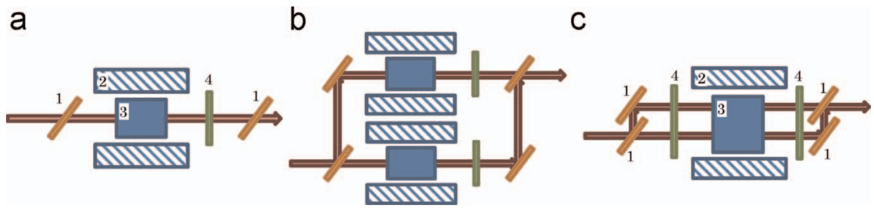

Fig. 1. FI schemes: (a) classical FI, (b) FI for nonpolarized light with two MOEs, (c) FI for nonpolarized light with one MOE. 1 (orange) – polarizers, 2 (hatched rectangles) – magnetic system, 3 (blue) – MOEs, 4 (green) – half-wave plates. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Faraday isolator schemes

The thermally induced depolarization γ arising in a FI under the action of the photoelastic effect was investigated in detail in a number of works [2,14]. MOE heating by laser radiation produces an inhomogeneous temperature distribution over its cross-section. The resulting temperature gradients give rise to elastic stresses in the medium and leaded to linear birefringence caused by the photoelastic effect. In the case of a classical FI scheme with polarized radiation (Fig. 1a), i.e. with axially symmetric MOE and an intensity distribution profile of the laser beam propagating strictly down the center of MOE, the analytical expressions for γ are also valid for the classical FI scheme with nonpolarized radiation (Fig. 1b) [12], in this case each channel is a separate axially symmetric FI. According to [2], thermally induced depolarization is proportional to the square of the laser power passing through the MOE. Therefore, simple division of the initial beam into two beams of equal power passing through different MOEs reduces the thermally induced depolarization by a factor of 4. It should be noted that the laser power losses with the scheme (Fig. 1b) with polarization beam splitting and combining don't exceed 3%, according to [12]. In the proposed scheme (Fig. 1c) power losses will not exceed this level.

However, when two beams pass through one element (see Fig. 1c), the distance between the beams may be chosen so that the temperature gradient is less, hence, the thermally induced depolarization will be reduced compared to the case when one beam of the same total power passes through the MOE center. Also this reduces thermal lensing effect, but astigmatism of arising thermal lens can be increased. To prove the idea numerical model was developed. Calculations were performed in three dimensions (x, y, z) coordinate space in three stages. Z axis is parallel to the laser beam propagation direction and the x and y axes are located in the orthogonal plane as well as the r axis. The first stage is the calculation of the temperature distribution in the sample by solving the heat equation taking into account boundary conditions on the side and end surfaces. The heat source in this case is calculated for a given heating radiation intensity profile by Beer–Lambert–Bouguer law. The resulting temperature gradients are used as a source of thermal expansion for elasticity equation. Next, from this equation in three-dimensional space with free boundaries conditions strain tensor is calculated. Heat and elasticity equations are solved by the finite element method (using a combination of Comsol and Matlab software systems).

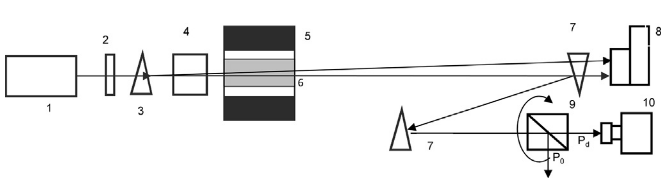

Fig. 2. Scheme of the experiment of thermal depolarization measurements: 1 – ytterbium fiber laser, 2 – halfwave plate, 3 – calcite wedge polarizer, 4 – reciprocal rotator, 5 – magnetic system, 6 – MOE, 7 – quartz wedges, 8 – radiation absorber, 9 – Glan prism, 10 – CCD-camera.

Then, the change of impermeability tensor elements $\mathbf{\Delta B}$ is calculated through elements of strain tensor ε. In the coordinate system associated with the crystallographic axes

$$\Delta\, B = p\varepsilon, \quad (1)$$

here $\mathbf{p}$ is photoelastic tensor. Further tensors are converted to the laboratory coordinate system that is rotated by the Euler angles θ, φ and ψ with respect to the system associated with the crystallographic axes of the sample. Then $\mathbf{\Delta B}$ is integrated along the beam axis; the Jones matrix and the local and integral depolarization degrees are calculated.

Analytical expressions for the thermally induced depolarization were obtained earlier for a traditional FI scheme (Fig. 1a) [2] as well as for FI with compensation of thermally induced depolarization [2,3]. For these cases, the results of modeling and the values obtained by analytical expressions are the same, this indicates accuracy of calculations.

The experimental scheme used in this study to measure the degree of depolarization is presented in Fig. 2. Linearly polarized radiation from a ytterbium fiber laser at the wavelength of 1070 nm passes through a half-wave plate 2 rotating the plane of polarization and then through a calcite wedge polarizer 3 with a small vertex angle, which separated the radiation into two beams, one with vertical and the other with horizontal polarization. The angle between the beams was 1.1 degrees, so they could be regarded to be almost parallel and nondiverging along the MOE length. Further, the beams passed through MOE 6 and were absorbed by a water cooled absorber 8. Part of the radiation from one of the beams was attenuated as a result of reflection from a pair of quartz wedges 7 and was then passed to a Glan prism polarizer 9 and to CCD camera 10 placed behind it. For measurements in a magnetic field the sample under test was placed in the magnetic system 5 of a traditional FI with inner diameter of 32 mm and average magnetic field strength of 1 T over the sample length. A reciprocal quartz polarization rotator 4 was placed in front of the MOE.

The depolarization γ was equal to the ratio of the radiation component that passed through the polarizer P_0 and the reflected component P_d.

To ensure the radiation intensity in each beam was equal, the MOE was replaced by a 0-degree mirror that reflected both polarizations equally. A CCD camera was then positioned after the mirror and, if necessary, halfwave plate 2 was adjusted to ensure the difference in intensity in the two beams did not exceed 2%. It was assumed that in view of symmetric passage of the beams through the element and their equal intensity, the level of depolarization in both beams was identical and equal to the total depolarization in the FI.

An important consideration when calculating the performance of the two-channel FI is the impact of the beam displacement from the center of a cylindrical MOE on the depolarization and, consequently, on the isolation ratio. The dependence of depolarization on beam displacement was measured in a gadolinium-gallium garnet (GGG) crystal with a diameter of 10 mm and length of

Please cite this article as: A. Starobor, O. Palashov, Optics Communications (2015), http://dx.doi.org/10.1016/j.optcom.2015.05.038