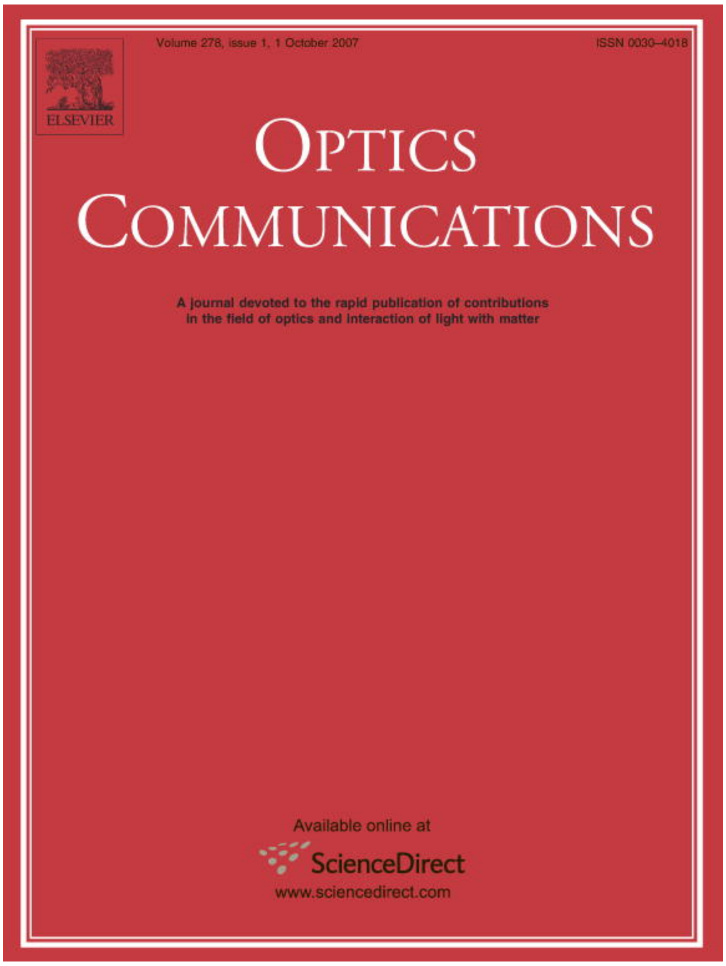
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Adaptive compensation of thermally induced phase aberrations in Faraday isolators by means of a DKDP crystal

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Abstract

In this paper, we describe adaptive compensation of thermal lens in a Faraday isolator using a DKDP crystal. Thermal lens measurements were made with a modification of the conventional Hartmann sensor – a 2D scanning Hartmann sensor. Our experiments showed that a DKDP crystal does not influence the isolation ratio of Faraday isolator and efficiently compensates for thermal lens. The negative effect produced by the thermal lens is estimated as the amount of power losses from the original beam mode (Gaussian mode in our experiments). Without compensation the losses were measured to be about 25% for 45 W radiation power and were compensated to less than 0.5% by a negative thermal lens in a 5.5 mm-thick DKDP crystal. Numerical extrapolation of experimental data to a higher power range has shown that for the powers up to 150 W, power losses can be made less than 5%.

1. Introduction

Optical distortions produced by radiation absorption are becoming more significant because of a continuous increase of the power of modern lasers. Some lasers available in the market today have already overcome the average power of 10 kW [1,2]. The high level of radiation power makes investigation and compensation of thermal effects one of the challenging tasks important for many modern optical systems. A lot of them employ a Faraday isolator (FI) for preventing damage to optical elements and sources of radiation. Laser Interferometer Gravitational-Wave Observatory (LIGO) project [3] is a good example of such systems for which high isolation ratio and minimum level of wavefront distortions are simultaneously required in a wide power range for a sustained period of time. Because of relatively high absorption coefficient of magnetooptical media FI characteristics are strongly affected by high power radiation. Investigation of thermal effects in FI and their minimization becomes more important because LIGO is expected to be upgraded [4] up to 180 W (Advanced LIGO).

Thermal lens in optical elements in most cases is considerably non-parabolic and depends on average power and intensity distribution of radiation. There are several ways of thermal phase distortions compensation like adding some objectives [5], producing additional heating of the sample [6,7] or employing glass [8,9] with negative thermal lens (in order to compensate for positive thermal lens in FI by negative thermal lens in the glass). In the latter case, both lenses have a common nature and compensation of non-parabolic part of the thermal lens is naturally achieved. Moreover, negative thermal lens adaptively follows the radiation power so there is no need in any movements in optical system to compensate for thermal lens in a wide power range. This is especially important when optical elements are placed in high vacuum conditions and mechanical movements are very difficult to implement. However, it was shown in [9] that photoelastic effect in compensating glass induces depolarization and high astigmatism of thermal lens. Both these effects reduce the efficiency of thermal lens compensation.

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In Ref. [9], in order to avoid these drawbacks, the use of uniaxial crystal instead of glass was suggested. By using natural anisotropy, it is possible to get simultaneously very small depolarization ratio and quite low thermally induced astigmatism. Low birefringence allows placing a compensating crystal maximally close to Faraday rotator (between rotator and polarizer) to make phase distortions not to propagate to intensity distortions.

In this paper, we have experimentally studied thermal lens compensation in FI by means of a DKDP crystal and demonstrated high efficiency of this technique. In the second section, we describe a 2D scanning Hartmann sensor which we developed and used for thermal lens characterization. The third section is devoted to the choice of DKDP crystal optical axis orientation. In the fourth section, results of thermal lens compensation are presented.

2. 2D scanning Hartmann sensor

To measure wavefront distortions produced by high radiation power, we used the so-called scanning Hartmann sensor (SHS) [10,11]. A typical Shack–Hartmann sensor [12,13] is one of the devices which is widely used in measurements of optical quality of elements and for studying wavefront distortions. The scanning Hartmann sensor described in this paper is its modification. The optical scheme of the sensor is shown in Fig. 1. A thin beam of probing radiation is directed by a scanning unit SU. After passing through objective L_1, sample S and objective L_2 the probing beam goes to the CCD camera. Mechanical movements of the scanning unit leads to parallel displacement of the probing beam in the area between L_1 and L_2 because SU is placed at the focal plane of objective L_1. Position of the beam center at the CCD camera actually reflects the propagation direction of probing radiation after the sample because CCD camera is placed at the focal plane of objective L_2.

Employment of a thin laser beam in scanning Hartmann sensor is the main modification as compared with typical Shack–Hartmann sensors. This modification makes it possible to use a single lens L_2 with rather large focal length instead of a matrix of small lenses and, as a result, to increase sensitivity (because sensitivity is proportional to F_2) and dynamic range of the sensor (because without neighbor spots, the spot has more room to move on CCD). This also eliminates diffraction effects on borders of small lenses of typical Shack–Hartmann sensors. Moreover, it is easy to select measurement resolution by changing scanning algorithm. These improvements are possible at the cost of a longer time required to scan the whole sample aperture. To increase scanning speed, the scanning unit SU is based on a galvanometer rotator (Cambridge Technology Inc., USA, Model 6450) which is quick and precise, simultaneously. The disadvantage of such a rotator is its inability to rotate a mirror in two dimensions. That is why the scanning Hartmann sensor was capable of obtaining only one-dimensional data [10,11]. Measurements of thermal lens in optical elements showed that one-dimensional scanning is not always adequate and convenient in the sense of setup alignment and interpretation of results (for example, in the case of asymmetrical thermal lenses).

To make the sensor more reliable and easier for alignment, it was proposed to upgrade the unit SU to the second dimension. At first, we planned to rotate the whole galvanometer mechanically around the horizontal axis. But then we understood that if we use large movable mechanical tables it is hard to make scanning process simultaneously precise, fast and stable.

To satisfy all these conditions, we used a second mirror rotating around the axis perpendicular to the axis of the first mirror (Fig. 1). The second mirror is also moved by galvanometer rotator. The only obstacle here is the impossibility to put rotation axes of both mirrors at the focal plane of L_1. Fortunately, numerical analysis showed that for misalignments of mirror's rotation axis from the focal plane (Δx) $\sim$ 1 cm precision degradation is about 1% only (with respect to phase distortion profiles and other parameters like F_1 (=35 cm) and F_2 (=65 cm) found in our experimental setup), (see Fig. 2). We succeeded to implement the distance between the mirrors less than 8 mm. Each mirror

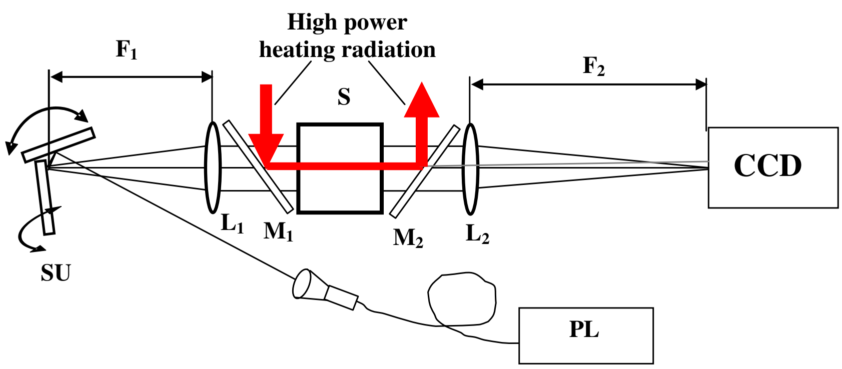

Fig. 1. Scanning Hartmann sensor optical scheme in measurements of thermal lens produced by high power radiation absorption in the sample: PL – probe laser; SU – scanning unit; L_1, L_2 – lenses; M_1, M_2 – 45° mirrors; S –sample.

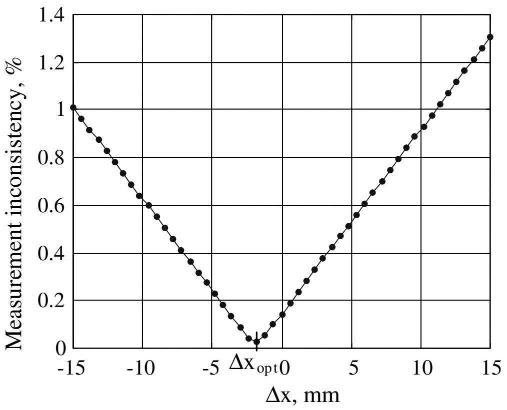

Fig. 2. Measurement inconsistency of scanning Hartmann sensor because of displacement of mirror's rotation axis and focal point of the lens L_1.

is based on galvanometer rotator, so we simultaneously obtained high rotation speed and accuracy. The assembled device was tested with a reference optical sample (with focus ≈ 60 m and curvature known with 5% accuracy) and demonstrated 2.5% focal length measurement precision and non-sphericity ~0.3%. More precise reference samples could reveal real SHS device precision but we do not check it because for our thermal lens measurements this precision is quite enough. Theoretical estimations based on camera noise measurements give for 20 mm aperture size and spherical wavefront: precision $\sim\lambda/200$ and phase measure range $\sim 10\lambda$ (i.e., ~5 m maximum lens curvature).

3. DKDP crystals as compensation element

To compensate for thermal lens in FI, we used DKDP because it seems most adequate for this task. First of all, it has negative thermal coefficient (dn/dT). DKDP is a uniaxial crystal and we expect negligible thermal depolarization in it. Measurements of depolarization ratio of DKDP crystal showed that it is about two orders of magnitude less than depolarization of FI and amounts to ~55 dB [14] . Moreover, it does not depend on laser power (for powers up to 200 W). That is why DKDP is better than glass for thermal lens compensation in FI. Compared to KDP crystals, DKDP has small enough absorption coefficient for 1 μm wavelength, so it is convenient to manufacture appropriate samples. For thermal lenses in investigated FI the thickness of DKDP samples should be several millimeters. In contrast to YLF, absorption coefficient in DKDP is large enough to have quite compact (and thus cheap) samples.

Thermal lens measurements were done with the 2D scanning Hartmann sensor. The experimental setup for measuring thermal lens compensation is shown in Fig. 1. Heating radiation is brought into the SHS tract by a 45° mirror M_1. The radiation passes through the sample and produces thermal lens in it and is then reflected by mirror M_2 which takes it away from the SHS tract. To make this optical scheme possible, probing radiation wavelength (0.85 μm) differs from heating radiation (1 μm) and coating of M_1 and M_2 totally reflects heating radiation and partly transmits probing radiation.

Unfortunately, because of the photoelastic effect, thermal lens in uniaxial crystals in the general case is anisotropic. On the contrary, thermal lens in TGG crystal used in FI is almost isotropic [9]. Our experiments demonstrated that it is possible to have a thermal lens in DKDP crystal isotropic enough to effectively compensate for thermal lens of the Faraday isolator (see Fig. 3) while preserving a low level of depolarization ratio. This is achieved by selecting the angle between the optical axis and the wave vector large enough to keep small depolarization and small enough to get isotropic thermal lens. As it is clear from Fig. 3, at an angle of 90° thermal lens is noticeably astigmatic and at an angle of ~30° (which is large enough to exclude thermal birefringence) thermal lens is quite isotropic.

4. Adaptive thermal lens compensation

In our experiments we used a wide-aperture FI based on terbium gallium garnet (TGG) magnetooptical crystals (clear optical aperture is 20 mm). To get high isolation ratio, the FI was assembled following the scheme with a reciprocal rotator [15]. According to this scheme, a 67.5°

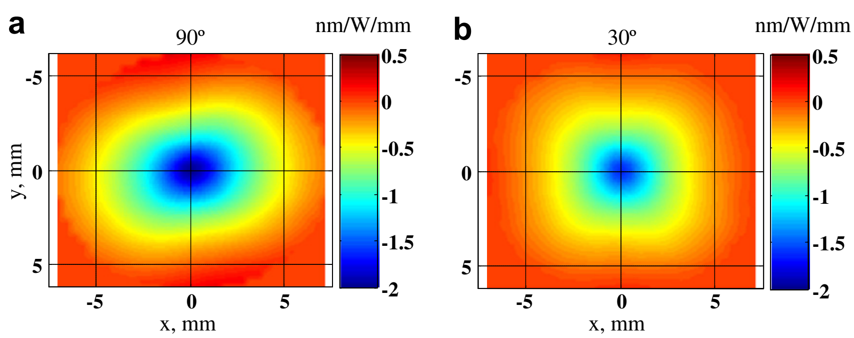

Fig. 3. Thermal lens anisotropy for two angles between the optical axis and the wave vector: (a) for angle equal to 90° and (b) 30°. Figures represent phase distortions of wavefront (in nm) normalized at radiation power (W) and DKDP crystal thickness (mm).

quartz rotator is placed between two identical TGG crystals. Each crystal rotates linear polarization by 22.5°. Direct measurements of depolarization ratio showed advantages of the scheme with reciprocal rotator [14–16].

Self-induced thermal lens is highly aberrational. To quantitatively characterize the thermal lens effect, we calculated the coefficient X of energy transformation from the fundamental Gaussian mode:

$$X = \left(1 - \frac{\left|\int E_0 E^* \mathrm{d}s\right|^2}{\int |E_0|^2 \mathrm{d}s \int |E|^2 \mathrm{d}s}\right),$$

where E_0 is the electric field of a Gaussian heating beam with flat phase, and E is the electric field after the optical element. The second term is the well-known overlapping integral. Coefficient X is a good characteristic of thermal lens because, at a first approximation it is independent of beam diameter [5].

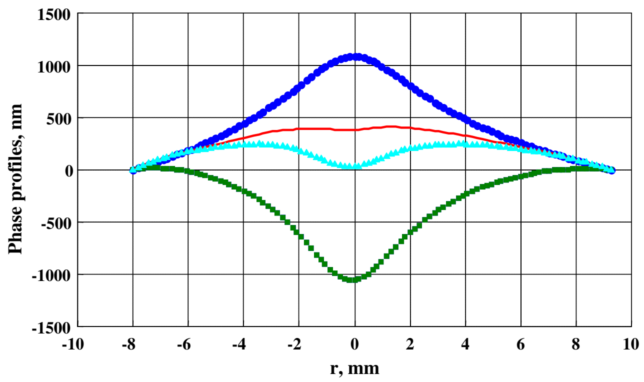

Fig. 4. Phase profiles of FI (circles), $X = 35\%$; of 5 mm-thick DKDP crystal (squares), $X = 63\%$; of both FI and 5 mm-thick DKDP crystal (triangles), $X = 11\%$; and of both FI and 3 mm-thick DKDP crystal (solid line), $X = 1\%$. Laser power 90 W, beam diameter ($1/e$ level) 2.8 mm.

It is necessary to note that parameter X is quite sensitive to E_0 profile. In our experiments parameters of Gaussian beam were calculated as optimal values, which maximizes fitting of Gaussian and measured intensity profile. The fitting was quite good (in most experiments the overlapping integral was more than 99.5%) and we did nothing to make the heating beam exactly Gaussian.

A first series of experiments was done with a 5 mm-thick DKDP crystal with angle between the optical axis and the wave vector equal to 40°. Yb:fiber laser (IPG Photonics) which delivers 100 W at 1064 nm wavelength with 2.8 mm beam diameter at $1/e$ level was employed as source of radiation. The results of these experiments presented in Fig. 4, demonstrated that the 5 mm DKDP greatly compensates for phase in the center. But unfortunately, the coefficient X in this case turned out to be 11%. This value is so high because the phase was not completely compensated in the beam area (except the exact center). To decrease power losses, we tried to model thermal lenses in DKDP samples of different thicknesses and to find an optimal thickness. As a result of this optimization, we found that in the case of optimal compensation (minimum of X) the DKDP element thickness should be about 3 mm. A compensated phase in the optimal case is also shown in Fig. 4. As compared to the experimental phase, the optimal phase is almost constant over the beam diameter; hence, X is much smaller. Power losses from the Gaussian mode in the optimal case are less than 1%.

Another series of experiments was done with Yb:fiber laser (IPG Photonics) delivering 50 W at 1076 nm wave-

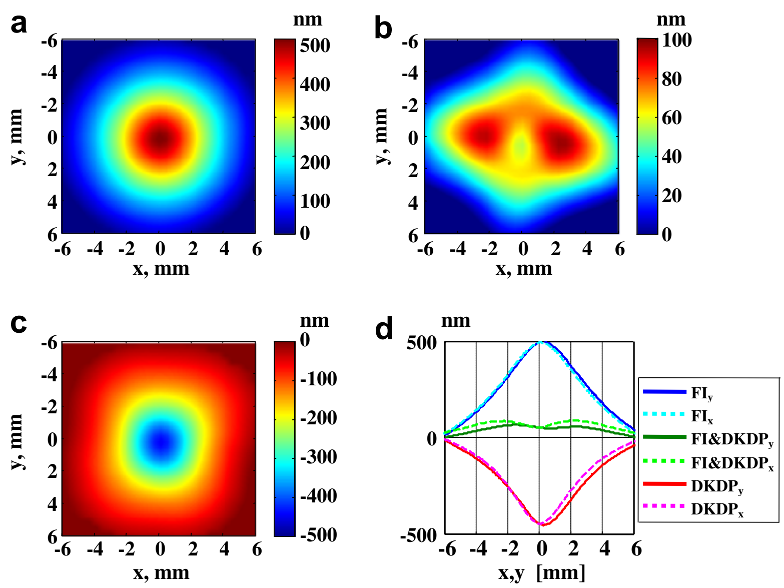

Fig. 5. Thermally induced phase map for Faraday isolator (a) DKDP crystal, (c) and both FI and DKDP (b) corresponding horizontal and vertical slices at the center (d).

Table 1
Calculated power losses X

Beam diameter = 4.5 mm	Thermal lens in Faraday isolator without compensation	Thermal lens in DKDP crystal	Thermal lens in FI compensated by DKDP crystal	Power losses for optimal DKDP thickness (calculation)
X, % at $P = 45$ W	26% (25 m)	24.1% (−27 m)	0.5% (630 m)	0.44% (1200 m)
X, % at $P = 200$ W	97.9% (5.4 m)	99.2% (−6.6 m)	9.3% (110 m)	8.2% (300 m)

For each cell of the table in brackets there is thermal lens focus estimation with method of momentums [17] in meters.

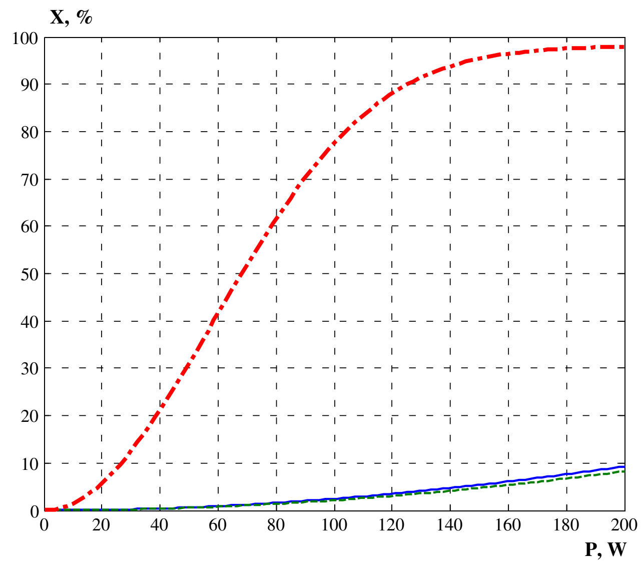

Fig. 6. Energy transformation from main mode coefficient X numerically extrapolated to a range of higher powers for Faraday isolator (dash-dot line), FI compensated by 5.5 mm-thick DKDP (solid line), FI compensated by 5.7 mm-thick DKDP (numerical optimization result, dash line).

length with 4.5 mm beam diameter at $1/e$ level. In this series we used 5.5 mm-thick DKDP crystal with angle between the optical axis and the wave vector equal to 30°. In Fig. 5, one can find 2D phase profiles for a FI, DKDP sample and both of them measured by the scanning Hartmann sensor for 45 W heating radiation. Table 1 summarizes the calculated power losses. Using experimental results, like for the first series of experiments, we calculated optimal DKDP thickness (amounted to 5.7 mm), corresponding phase distortion and minimal possible X, (last column in Table 1).

To find compensation effectiveness for larger powers, we extrapolated the thermal lens profiles in the power range up to 200 W on the basis of their experimental profiles for 45 W. We assumed that thermal phase is linear to the power of heating radiation. This assumption is valid at moderate thermal loading while the material constants (thermoconductivity, expansion coefficient, etc.) do not depend on temperature. The calculated power losses as a function of laser power are shown in Fig. 6. The graphs demonstrate that even for 200 W laser power when power losses are 98%, the adaptive compensation can decrease losses down to a reasonable level of 8.2%.

5. Conclusion

The implemented 2D scanning Hartmann sensor based on scanning unit with two mirrors with perpendicular rotation axes has proven to be a convenient and adequate device for measuring thermal distortions in optical elements. With galvanometer rotators used as moving mechanism, high speed and accuracy can be simultaneously achieved.

We have experimentally demonstrated high efficiency of adaptive compensation of thermal lens in Faraday isolator by means of DKDP crystals. We experimentally demonstrated that for 45 W laser power the compensation allows reducing power losses in Gaussian mode X from 26% to 0.5%. Estimations have showed that losses can be reduced to a level of 4.7%, even for a laser power of 150 W.

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