In-vacuum optical isolation changes by heating in a Faraday isolator

The VIRGO Collaboration

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Received 14 February 2008; revised 12 August 2008; accepted 20 August 2008;
posted 21 August 2008 (Doc. ID 92581); published 28 October 2008

We describe a model evaluating changes in the optical isolation of a Faraday isolator when passing from air to vacuum in terms of different thermal effects in the crystal. The changes are particularly significant in the crystal thermal lensing (refraction index and thermal expansion) and in its Verdet constant and can be ascribed to the less efficient convection cooling of the magneto-optic crystal of the Faraday isolator. An isolation decrease by a factor of 10 is experimentally observed in a Faraday isolator that is used in a gravitational wave experiment (Virgo) with a 10 W input laser when going from air to vacuum. A finite element model simulation reproduces with a great accuracy the experimental data measured on Virgo and on a test bench. A first set of measurements of the thermal lensing has been used to characterize the losses of the crystal, which depend on the sample. The isolation factor measured on Virgo confirms the simulation model and the absorption losses of $0.0016 \pm 0.0002/\mathrm{cm}$ for the TGG magneto-optic crystal used in the Faraday isolator. © 2008 Optical Society of America

OCIS codes: 140.6810, 230.2240.

1. Introduction

In all currently operated gravitational wave interferometers [1–4], a lot of attention is dedicated in reducing as much as possible any disturbance and noise reintroduction produced by spurious beams and parasitic reflections. In particular, the frequency stability of beam incoming in the interferometer is affected by the main backreflection of the interferometer itself towards the injection system. Faraday isolators (FIs) are placed on the external (in-air) laser and optical benches in order to prevent light reflected by the interferometer and injection optical components from going back into the laser. The geometry of injection cavities, in particular the in-vacuum input mode cleaner cavities (IMCs), is triangular, with the aim to spatially separate the forward-circulating beam from the back-circulating one. However, even in the triangular geometry, a small portion of the backreflected light is scattered inside the IMC and couples with the forward-traveling beam, thus producing disturbances in the IMC control loops. A further optical isolation is therefore achieved by placing an optical isolator (a FI) inside the vacuum vessel, between the IMC and the interferometer, in order to prevent the interferometer backreflected light from getting into the IMC. This FI is therefore operating in a 10^{-6} mbars vacuum environment, and it has to accommodate a beam having a several millimeter diameter size and several watts of power. Due to the quite large light intensity in the Faraday crystal, thermal effects may become an issue. Induced thermal lensing [5], resulting in beam/interferometer mismatching, was considered the main possible disturbance introduced by these devices, in particular considering that the amount of light going through them would change according to the resonance conditions of the interferometer and to possible needs to operate at different input powers. These effects have actually been taken into account and limited as much as possible by selecting Faraday crystals with low absorption: terbium gallium garnet (TGG) crystals with absorption in the range of $0.002/\mathrm{cm}$ are used accordingly. Passive thermal lensing compensation systems have been proposed [6]

0003-6935/08/315853-09$15.00/0

and will become crucial in future applications with higher intensity input beams. A worsening of the optical isolation of the FI, caused by thermally induced depolarization [7], will also become critical in larger power applications and require a dedicated designed FI [8].

2. Vacuum Effects in Faraday Isolator Isolation

Another effect, which has not been expected to be significant with the actual input laser power, is the change of the optical isolation of the FI when passing from air to vacuum: simulations show that FIs, which are manually tuned in air, may change their optical isolation power significantly once put in vacuum. This effect can be ascribed to several sources: a (Matlab) finite element model (FEM) simulation has been developed by the authors in order to model the effect. The simulation takes the absorption of the crystal, the thermal heating, and the heat dissipation mechanisms into account. The conclusions of this study would explain the isolation change in terms of different heating of the TGG crystal by the incoming beam when passing from air to vacuum, where the thermal dissipation of the air convection is absent. The predictions of this model were first observed in the Virgo interferometer, where the optical isolation of a FI drops from more than 40 dB to about 29 dB once the FI is put in vacuum. The optical isolation degradation is not seriously affecting the functioning of the interferometers at the present performance level but will become more important in the next upgrades, when a larger amount of power will be used, and as a consequence more significant thermal effects will occur if no correction system is designed.

3. Simulation

A. Simulation Model

To simulate the effect of heat in a FI, we have developed a FEM simulation using Matlab. This model computes the absorbed energy from a heating Gaussian beam and makes a map of temperature using the thermal conduction law inside and the Stefan–Boltzmann law at the limits of the heated crystal (see Fig. 1).

The crystal is not fully in contact in its magnetic housing, but there is only a thin ring touching it, and a space remains for the majority of its surface. As convection has a nonnegligible effect in this space, we use an empirical model of convection [Eq. (1)]. This model has a free parameter $b = [10 : 100]$ corresponding to the turbulent case ($b = 10$) and the laminar case ($b = 100$). For in-air simulations, all our simulations consider that we are in turbulent conditions (i.e., $b = 10$) since we surely do not have a laminar flux between the TGG crystal and the shield. We also consider that all the radiated energy from the crystal is absorbed by the shield, simplifying the effect of the space between crystal and shield:

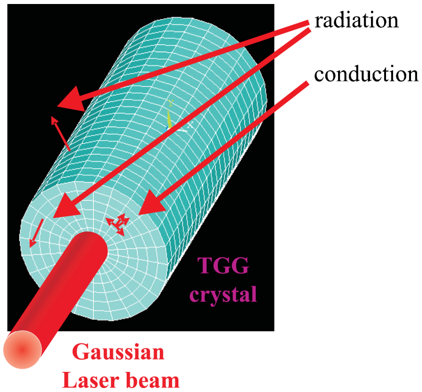

Fig. 1. (Color online) Picture showing the mesh for FEM simulation in the crystal and in the surrounding medium to be studied.

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = b(T - T_{\mathrm{ref}})\mathrm{d}S, \qquad (1)$$

where Q is the heat, $\mathrm{d}S$ is a small surface element, T is the temperature, and T_{ref} is the temperature of the TGG crystal when there is no laser beam passing through it.

The FEM simulation gives as output a temperature map of the crystal from which we can construct

- the refraction index map defined by the $\frac{\mathrm{d}n}{\mathrm{d}T}$ factor,
- the geometrical expansion defined by the thermal expansion factor,
- the isolation factor defined by temperature linear variation of the Verdet constant and the change of length.

FI isolation ratio decrease due to self-induced depolarization is mainly due to two mechanisms that alter the polarization of the laser beam transmitted through the TGG rod and then affect the isolation ratio of the FI [7].

- The first is a nonuniform distribution of the rotation angle of the polarization plane caused by the temperature dependence of the Verdet constant.
- The second is due to the simultaneous appearance of circular birefringence (Faraday effect) and linear birefringence (due to the photoelastic effect of thermal strains in the crystal) caused by temperature gradient (due to laser beam heating).

In this paper, we assume that the most important contribution is due to the temperature dependence of the Verdet constant. This is supported by the consideration that in a vacuum, the Faraday rotation angle is turned away from the minimum depolarization value. This assumption is actually consistent with the simulation results as you will see in Section 4.

B. Simulation Results

To check the reliability of our simulation, we have successfully reproduced experimental data of a heated TGG crystal presented in Refs. [9,10]. A particularly critical parameter to simulate the thermal heating of a TGG crystal is the substrate absorption losses. This parameter depends on the sample and can vary from a factor 1 to 4 according to the provider. To define better this parameter, we have experimentally reproduced the heating behavior of our Virgo FI with a 20 W single-mode single-frequency Nd:YAG laser beam with two different values of waist size: 1.1 mm and 2 mm.

The in-vacuum Virgo FI is a commercial Electro-Optics Technology vacuum-compatible FI, including two Karl–Lambrecht input and output thin-film Brewster polarizers. The rotating crystal is a TGG cylinder, 1.8 cm long and 2 cm in diameter. The crystal is inserted in a conical housing inside the magnet and held by the magnetic field itself (about 1 T). Thus, the crystal is touching the housing with only one of the two circular edges. The thermal lensing effect produced by the heating of the TGG in its housing has been measured with a Shack–Hartmann analyzer. The results, given by the Shack–Hartmann, are measurements strongly dependent on the size of the pupil analyzed, thus giving a nonnegligible uncertainty on these measurements. In Fig. 2, we compare the radius of curvature of the output face (equivalent to the thermally induced focal length) of the TGG for different losses and the experimental results. Solid and dashed lines have been obtained using an analytical formula that gives a first approximation of the equivalent focal length induced by laser beam heating [11], by neglecting stress and thermal expansion effects:

$$f = \frac{\pi \kappa w^2}{L \alpha P (\mathrm{d}n/\mathrm{d}T)}, \tag{2}$$

where w is the pump beam radius (waist inside the crystal), P is the pumping power in watts, n is the refractive index of the TGG crystal, α is the absorption losses, $\mathrm{d}n/\mathrm{d}T$ is the temperature coefficient of the refractive index, and κ is the thermal conductivity.

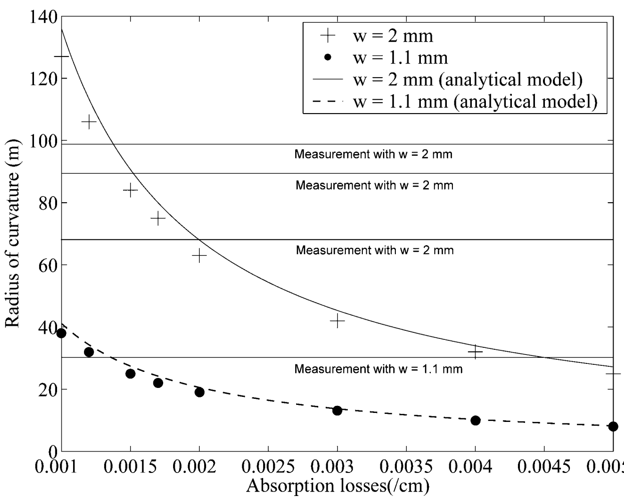

Fig. 2. Simulation of the thermal lensing effect for a TGG crystal with a diameter of 20 mm and a length of 18 mm. The lines represent experimental results done with a 20 W Nd:YAG laser with a waist of 1.1 mm and 2 mm. Solid and dashed lines correspond to the radius of curvature computed with the analytical model given in Eq. (3).

In our case, the radius of curvature is

$$R = nf/2 = \frac{n \pi \kappa w^2}{2 L \alpha P (\mathrm{d}n/\mathrm{d}T)}. \tag{3}$$

For TGG crystal, $\kappa = 7.4\,\mathrm{W/m/K}$, $n = 1.95$, and $\mathrm{d}n/\mathrm{d}T = 19 \times 10^{-6}$ (given by the manufacturer Northrop Grumman).

This formula gives a good approximation for the radius of curvature R when w is much smaller than the crystal diameter as shown in Fig. 2.

The measurements with the 2 mm waist give for the radius of curvature an upper limit of 68 m and a lower limit of 99 m. From these results, we can deduce a value of $0.0016 \pm 0.0002/\mathrm{cm}$ for the TGG absorption losses. In Fig. 2, the measurements with 1.1 mm waist size confirm the absorption losses estimation.

4. Optical Isolation Measurement

The predictions of the model have already been confirmed on the Virgo interferometer. The Virgo in-vacuum FI is placed between the 144 m long IMC and the interferometer on an in-vacuum suspended bench. The incoming beam has a power of about 10 W and a waist size of 2.6 mm inside the TGG crystal. The free aperture of the FI is 20 mm, in order to avoid beam clipping and diffraction problems. The power of the interferometer reflected beam can be up to 9.5 W, depending on the interferometer working resonance condition. The FI has been installed in this position after it was previously observed in the Virgo experiment that the light coming back from the interferometer, once the power recycling mirror (PR) is aligned, disturbed the IMC locking control. The consequence is an increase in the frequency jitter of the beam entering into the interferometer. The increase in noise was large enough to prevent the locking of the power recycling cavity. Actually, this problem was solved by inserting a FI isolator on a suspended injection bench (SIB) in vacuum between the IMC and the interferometer as shown in Fig. 3.

Then, the FI was installed on the SIB and tuned in air, sending about 7 W of the main Virgo laser beam through it. We autocollimated the PR reflection by aligning the PR mirror. In this configuration, we reflected back 95% of the input beam. The optical isolation was tuned by adjusting the half-wave plate placed before the FI and the FI input polarizer rotation and looking at the power measured by a monitoring photodiode close to the main Virgo laser. The signal coming from the monitor was the reflection of another Faraday isolator (LB FI) placed in front of the main laser, which was essentially all the power coming back towards the laser system that had not been stopped by the SIB FI (see Fig. 3). In this way, the tuning was considered satisfactory when

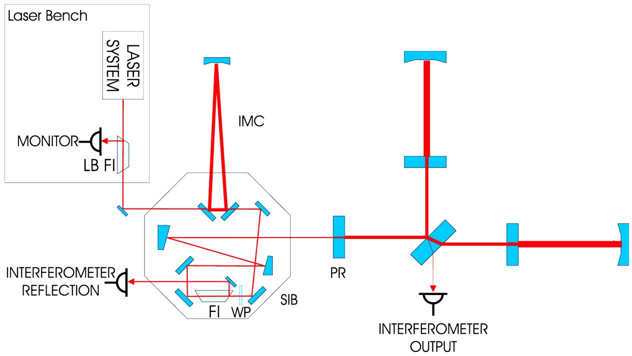

Fig. 3. (Color online) Scheme of the Virgo interferometer: the Faraday isolator (FI) is placed on the suspended injection bench (SIB) in vacuum between the input mode cleaner (IMC) and the interferometer.

the maximum power of the beam reflected towards the laser system (when the PR was aligned) was reduced by about 40 dB. The tuning of the FI had been performed in an alignment condition essentially coincident to the Virgo operating one. After the in-air tuning operation, the SIB was put in vacuum, the IMC was locked, and the interferometer operated again. Again, we compared the change of power measured by the monitoring photodiode when PR mirror is aligned. In Fig. 4, the simulated isolation factor is given for in-air and in-vacuum operation of the SIB FI function of the TGG absorption losses.

- For the in-air configuration (curve with crosses), we considered that the crystal was heated by a 13.65 W Nd:YAG laser. The horizontal error bar corresponds to the experimental isolation measurement.
- For the in-vacuum configuration (curve with dots), we considered that the crystal was heated by a 19.5 W Nd:YAG laser. The horizontal error bar corresponds to the experimental isolation measurement.

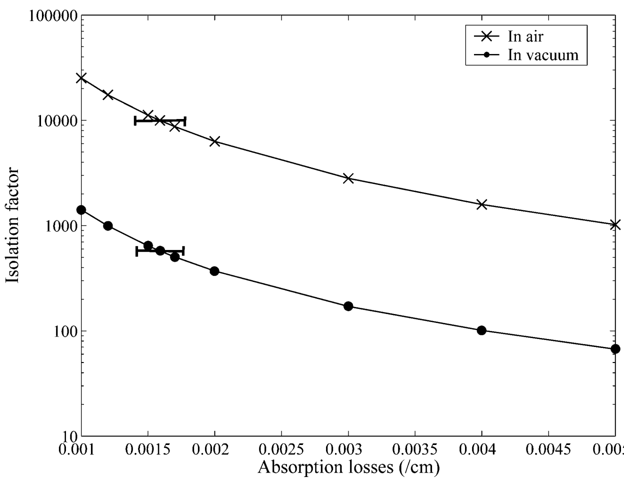

Fig. 4. Simulation of the isolation factor for a TGG crystal with a diameter of 20 mm and a length of 18 mm heated by a 13.65W (in air) and 19.5W (in vacuum) Nd:YAG laser.

The results reproduce well the decrease of isolation that occurs when the FI is placed in vacuum. This effect is mainly due to the lack of convection between the crystal and the housing when in vacuum compared to the optimum tuning done in air. The value of losses around 0.0016/cm for the TGG is also confirmed (see Fig. 4) and explains a nearly nondetectable thermal lensing effect. The residual part of the laser power passing through the SIB FI has been measured by the monitoring photodiode (see Fig. 5). We get 12 mW of backreflected mean power on the laser bench with a power of 19.5 W crossing the SIB FI ($P_{\mathrm{in}}(=10\,\mathrm{W}) + 0.95\,P_{\mathrm{in}}(P_{\mathrm{ref}})$). This corresponds to an optical isolation of the FI smaller than 29 dB.

5. Conclusion

In this paper, we demonstrated that the 10 dB isolation factor decrease of a Faraday isolator under vacuum is due to the heating of the TGG crystal by the laser beam. Under vacuum the strong degradation of the isolation factor is attributed to the less efficient convection cooling of the absorbing optical elements of the FI. The decrease of the isolation factor of a FI measured in Virgo interferometer between a fine tuning made in air and its final working condition under vacuum is well reproduced by a FEM simulation. The results are in concordance with losses of 0.0016 ± 0.0002/cm for the TGG crystal used in the FI. The decrease of isolation shows the necessity to install a fine remote tuning of the FI. In Virgo, an additional remotely tunable rotating wave plate will be added in the FI after the first polarizer to compensate this loss of isolation. Our results also demonstrate the interest of using low losses magneto-optic crystal to lower the thermal effects and reduce the FI loss of isolation. As new upgrades for gravitational interferometers will increase their laser power by a factor of 2 to 10, these effects will become critical and a thermal compensation

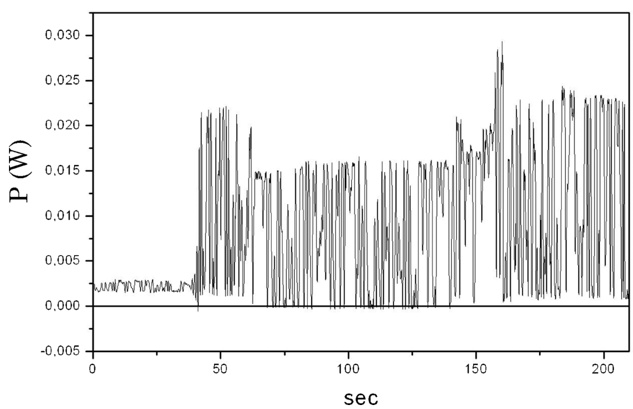

Fig. 5. Residual part of the laser power not stopped by the SIB FI going back to the Virgo laser.

system will be necessary to allow the system to work at any power [12].

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