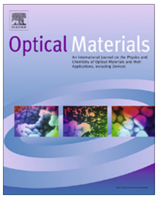
Optical Materials 46 (2015) 526–529

Contents lists available at ScienceDirect

Optical Materials

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



Characterization of the terbium-doped calcium fluoride single crystal

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ARTICLE INFO

Article history:
Received 27 January 2015
Received in revised form 20 April 2015
Accepted 8 May 2015
Available online 29 May 2015

Keywords:
Optical materials
Faraday effect
Thermally induced depolarization
Cryogenic cooling

ABSTRACT

Optical, thermo-optical and magneto-optical characteristics of the terbium-doped (10 at.%) calcium fluoride sample were investigated. It was made the analysis, confirmed the possibility of development of a Faraday isolator and a cryogenic Faraday isolator based on the studied medium, which will provide more than 30 dB isolation ratio of laser radiation in the “eye-safe” wavelength range (1530–1620 nm) at the 5 and 20 kW power, respectively.

1. Introduction

In the view of the lasers rapid development and the average power growth of both continuous and pulsed-periodic radiation, the issue of reducing of thermal effects, which appears in different optical elements due to the laser radiation absorption, becomes more and more actual. Faraday isolators (FIs) are optical devices in which the radiation is subjected to strong thermal self-action (due to relatively high absorption coefficient of the FIs magneto-optical elements (MOEs) $\sim 10^{-3}\,\text{cm}^{-1}$) [1–4]. Caused by absorption the temperature non-uniform transversal distribution leads to the inhomogeneous polarization plane rotation angle distribution (due to the temperature dependence of the Verdet constant), to the appearance of the linear birefringence along with the Faraday effect (photoelastic effect) and to distortions of the passed through the FI radiation wavefront (thermal lens) [5].

Depolarization, caused by the radiation absorption in the optical elements and called “hot” or “thermally induced” significantly depends on the radiation power and can greatly exceed the “cold” one which arising due to the magnetic field inhomogeneity and the MOE imperfection. In a cubic crystal with orientation [001], depending on the angle between the crystallographic axis and the radiation polarization, the thermally induced depolarization has maximum and minimum values defined by formulas [6]:

$$\gamma_{\min} = \frac{A}{\pi^2}\left(\frac{\alpha Q L P}{\lambda \kappa}\right)^2 \quad (1)$$

$$\gamma_{\max} = \frac{A}{\pi^2}\left(\frac{\xi \alpha Q L P}{\lambda \kappa}\right)^2 \quad (2)$$

where α, κ – the absorption and thermal conductivity coefficients, L – the MOE length, P – the radiation power, λ – the radiation wavelength, Q – the thermooptical constant [7], A – the numerical coefficient, depends on the crystal orientation and laser beam profile (for the orientation [001] and a Gaussian beam $A = 0.137$ [6]), ξ – the optical anisotropy parameter (for amorphous media $\xi = 1$).

The Verdet constant of paramagnetic materials is increasing with the cooling [8–11]. Furthermore, other thermooptical characteristics are improving with the temperature decreasing. This fact was the reason for the development of the cryogenic FI (CFI) – the device which MOE and magnetic system are cooled to the liquid nitrogen boiling temperature [8,12,13]. As long as, magnetoactive media parameters change on cooling [9,14,15], traditionally used in the FIs media (e.g. terbium gallium garnet (TGG) crystals), being applied in CFI may concede to some new media.

In recent years, with the development of ceramics and single crystals manufacturing techniques the number of magnetoactive media for developing FIs for high average radiation power was considerably increased. Basically, such media (for example, terbium aluminum garnet (TAG) and terbium aluminum garnet doped with cerium (Ce:TAG) ceramics, terbium–scandium aluminum garnet (TSAG) single crystal), are exceed the TGG by the Verdet constant value. The good performance of FIs based on such media [16–18] in the kilowatt power range is provided by the MOE shortening and therefore, according to (1, 2), decreasing of the thermally induced radiation distortions. However, this approach to the optimal magnetoactive medium selection is not the only one – in

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http://dx.doi.org/10.1016/j.optmat.2015.05.018
0925-3467/

present paper, it was characterized the sample of optical medium selected by alternative principle.

Calcium fluoride (CaF_2) is a well-known cubic single crystal medium used for the ultraviolet and infrared microscopy and spectroscopy optical windows, lenses and prisms development. The advantages of this medium are the refractive index decrease with the temperature increasing ($dn/dT < 0$, that makes it promising for the thermal lens adaptive compensation applications), high transparency of the material at an extremely wide wavelengths range (150–9000 nm, that makes it promising for use in near and middle-IR devices), high thermal conductivity (10 $\frac{W}{m\cdot K}$, that makes it promising for use in high average radiation power devices). However, the capability of using this medium in FIs and CFIs is significantly limited by the fact that pure calcium fluoride is diamagnetic and hence has an extremely low Verdet constant (0.025 $\frac{deg}{kOe\cdot cm}$ [19]).

A number of papers show that the paramagnetic nature of many optical media is stipulated by the presence in their structure of rare earth metals ions, especially terbium [19,20–22]. The present paper gives the optical, magneto-optical and thermo-optical characteristics measurements results of the new medium – calcium fluoride doped with terbium ions (10 at.%). 10 at.% is the almost maximum terbium ions percentage, which still retained the cubic crystal structure of the medium (from the crystallographic point of view, the results of calcium fluoride doping by some rare earth metals ions are presented in [7,23]). In present paper, it is shown that with such doping the CaF_2 medium reveals the paramagnetic properties that are sufficient for creation of high-power FIs, based on the available magnetic systems [9,24].

2. Experimental results

2.1. Transmission spectrum

The growth of Tb:CaF_2 sample was made by traditional technique, first suggested by Bridgman and improved by Stockbarger. This technique is used successfully (about 40% of production of artificial crystals) because it is a simple technology and does not require complicated control systems. The Tb:CaF_2 crystal was obtained by adding TbF_3 to the melt in concentrations which results in 10 at.% terbium ions consistence in final medium. The feature of the growth process was that it was made without scavengers, the furnace chamber was vacuumed to 10^{-1} Pa; the temperature was kept at 100 °C for 3 h to remove water from the raw materials and then 3 h at 800 °C to eliminate the possible admixtures.

After that, it were defined the crystallographic axes direction by the X-ray diffractometry method. Then the Tb:CaF_2 sample with orientation [001], 10.3-mm diameter, 29-mm length was cut and polished.

Using the ellipse-meter LEF-3M-1 the studied medium refractive index was measured, amounted to 1.465 for red light ($\lambda = 633$ nm), while the refractive index of pure calcium fluoride at this wavelength – 1.432.

The medium transmission spectrum was measured using a spectrophotometer SF-256 UVI (300–1100 nm wavelength range) and a spectrophotometer SF-256 BIK (1100–2200 nm wavelength range). The results are shown in Fig. 1 (solid line) compared with transmission spectrums of pure CaF_2 (dotted line) and TGG (dot-dashed line) crystals. The presence of terbium ions leads to high (but still not as high as in TGG) absorption at 485 nm and in the longer than 1600 nm wavelength range, but in the 500–1600 nm range the transmittance change is within the instrumental error. Especially draws attention the fact that Tb:CaF_2 retains high transparency in longer wavelengths range than the traditional TGG crystal, which opens up prospects of its use for erbium-doped fiber lasers wavelengths range ("eye-safe" range 1530–1620 nm) becoming more popular lately [25–27].

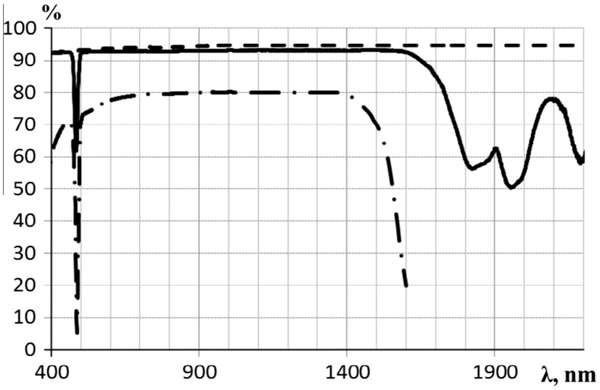

Fig. 1. Transmission spectrums of TGG crystals (dot-dashed line), CaF_2 (dashed line) and Tb:CaF_2 (solid line).

2.2. Verdet constant

To investigate the magnetooptical characteristics of the terbium doped calcium fluoride sample a compact magnetic system made of Nd–Fe–B permanent magnets was used. Direct measurements of the magnetic field strength longitudinal component (which cause the linearly polarized radiation polarization plane rotation) were carried out using the "Mayak-5" teslameter, which probe was moved along the axis of the magnetic system using a stepper motor. The measured values of the magnetic field were automatically recorded each 0.5 mm. The results are presented in Fig. 2.

In order to research the dependence of Verdet constant on the laser radiation wavelength it were used five semiconductor and one solid-state lasers, which together overlap the wavelengths range from visible light purple border to near-IR range. The exact wavelength of each source radiation were measured by using a spectrometer "Solar TII S-150-2" and were amounted to 405 ± 2 nm, 532 ± 2 nm, 633 ± 3 nm, 810 ± 1 nm, 1076 ± 1 nm, 1300 ± 1 nm.

The Verdet constant was calculated by measuring the laser radiation polarization plane rotation angle. The measurements were conducted in the experimental setup shown in Fig. 3.

The radiation of laser 1 passed the polarizing filter 2, linearly polarized, passed through the studied optical medium 3, placed in a magnetic system 4, was directed to a polarizing filter 5, placed on the limb table, and was detected by CCD-camera 6. The polarization plane rotation angle was measured by turning the polarizing filter 5 from a position when the planes of polarizing filters transmitted polarizations are orthogonal to the position when the signal on the camera 6 is minimal (which is mean that the

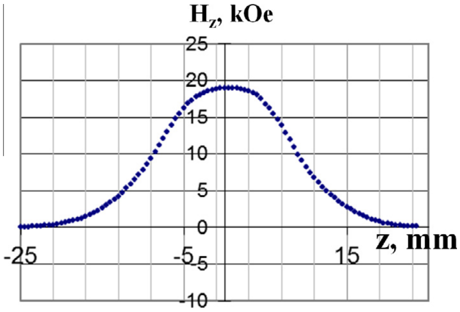

Fig. 2. The spatial distribution of the magnetic field longitudinal component.