The Optical Properties of Yttrium Iron Garnet Crystals in the Near Infrared

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In this paper the optical properties of pure $Y_3Fe_5O_{12}$ single crystals in the near infrared are presented. The transmission and refractive index have been measured in the spectral region 1–2.5 μm at the room temperature. The absorption coefficients were calculated from these data. Our data are compared with the results of other papers.

Introduction

The possibility of using laser in communication systems contributed greatly to the development of the modulation techniques of the light. Many modulation methods have been investigated over past years [3], [6] and, among them, the use of magneto-optic effect (Faraday's effect) in the ferromagnetic materials was one of the most successfull aplications. The most interesting material in the near infrared region seems to be Yttrium Iron Garnet crystal. The application of the $Y_3Fe_5O_{12}$ crystals as the modulating medium in magneto-optic modulators induces great interest and intensive research works for better knowledge and utilization of this material.

Detailed determination of the optical parameters of these crystals is highly recommended since the appropriate publications [1], [2], [4], [5] contain significant divergences in experimental results.

This paper presents experimental data of the refractive and absorption measurements in pure $Y_3Fe_5O_{12}$ single crystals. All measurements were carried out at the room temperature. The obtained results have been compared with the data of the publications [1], [2], [4], [5].

Experimental procedure and results

Preparation of samples

The crystals used for measurements have been synthetized in the Ferromagnetic Laboratory of Institute of Physics, of Polish Academy of Sciences and in the Central Institute of Optics and Spectroscopy of the German Academy of Sciences – Berlin (German Democratic Republic).

The single crystals were x-ray oriented in the direction [111]**. The crystals were cut in such a manner that direction [111] was always perpendicular to the surface of the samples. The samples were ground and polished in the customary way to obtain satisfactorily good optical surfaces. The thicknesses of the samples were 1 mm and their areas approx 0.2 cm².

Measurements of the refractive index

The refractive index was measured in the spectral region from 1 to 2.5 μm employing the microscope [7]. The measurements were carried out by means of the arrangement consisting of a source of radiation, a monochromator, a microscope, a PbS detector, a narrow band amplifier, a phase detector, and a recording voltmeter.

The refractive index were calculated from formula:

$$n = \frac{d}{d-x}, \tag{1}$$

where

d — thickness of the sample,

x — displacement of the objective lens of the microscope.

The results of the refractive index measurements are given in Fig. 1.

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** Orientation of the crystals is not obligatory because $Y_3Fe_5O_{12}$ possesses cubic symetry — space group O_h^{10}.

The results of the measurements of the samples done in Poland and Germany agreed satisfactorily with the data which may be found in the paper [4].

The error of measurement $\Delta\eta$ was estimated statisticaly. It turned out that $\Delta\eta \leqslant \pm 0.1$ (relative error $\Delta\eta/\eta$ approx 4.5 %).

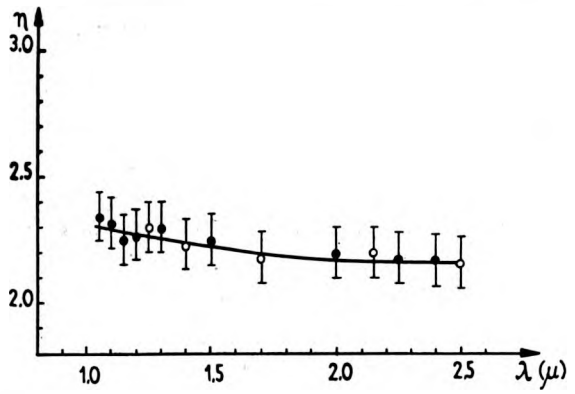

Fig. 1. The dependence of the refractive index on wavelength for pure $Y_3Fe_5O_{12}$ crystals
● – The results of the measurements of the samples done in Poland,
○ – The results of the measurements of the samples done in Germany.

Measurements of the transmission and determination of the absorption coefficients

The transmission was measured in the spectral region from 1 to 2.5 μm using "in-out" technique. The measurements were carried out by means of an optical system consisting of a SPM-1 Zeiss monochromator equipped with glass prism, a PbS detector, a narrow band amplifier operating at 384 Hz, a phase detector and a recording voltmeter. The samples were placed before monochromator. The transmission was measured with spectral resolution (spectral width of the monochromator) about $\Delta\lambda \approx 20$Å. The accuracy of these measurements was estimated to be about ± 0.01. The results of the transmission measurements are shown in Fig. 2. The absorption coefficient was calculated using the formula

$$T = \frac{(1-R)^2 e^{-ad}}{1-R^2 e^{-2ad}}, \qquad (2)$$

where

a — absorption coefficient,
R — coefficient of the reflectivity,
d — thickness of the sample,

which takes account for multiple internal reflections within the sample.

The coefficient of reflectivity was calculated from the formula:

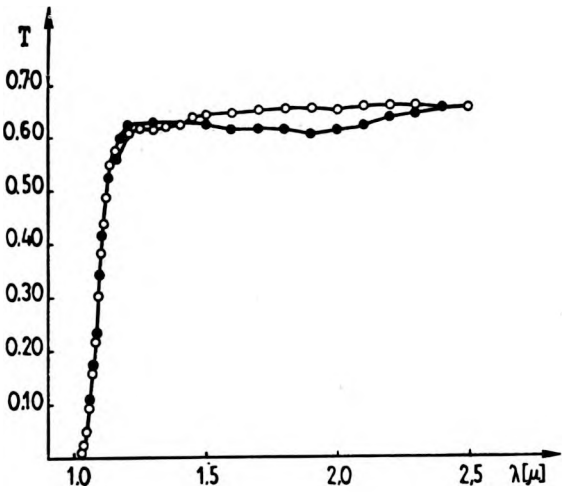

Fig. 2. The resu ts of transmission measurements on $Y_3Fe_5O_{12}$ crystals
● – The measurements of the samples done in Poland,
○ – The measurements of the samples done in Germany.

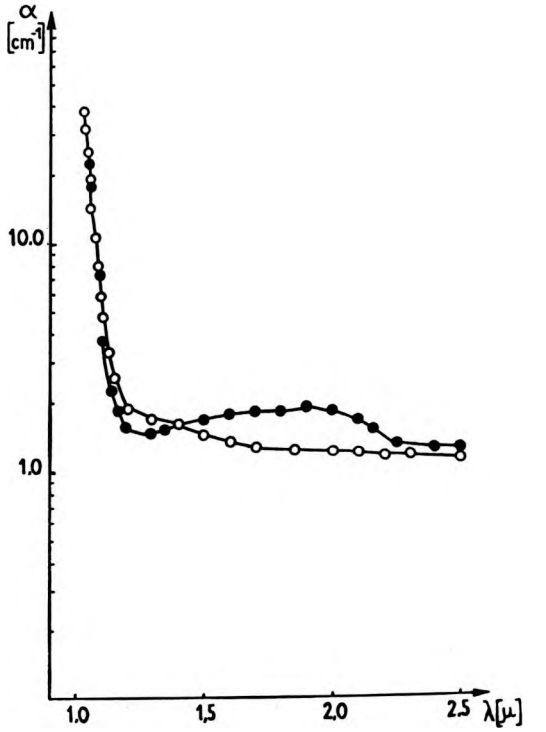

Fig. 3. The dependence of the absorption coefficient on wavelength for pure $Y_3Fe_5O_{12}$ crystals:
● – The results of the measurements of the samples done in Poland,
○ – The results of the measurements of the samples done in Germany.

$$R = \left(\frac{n-1}{n+1}\right)^2. \qquad (3)$$

In formula (3) the coefficient of extinction $\varkappa$ was neglected, because $\varkappa < 10^{-2}$ in the investigated region.

The results of the absorption coefficients obtained are shown in Fig. 3.

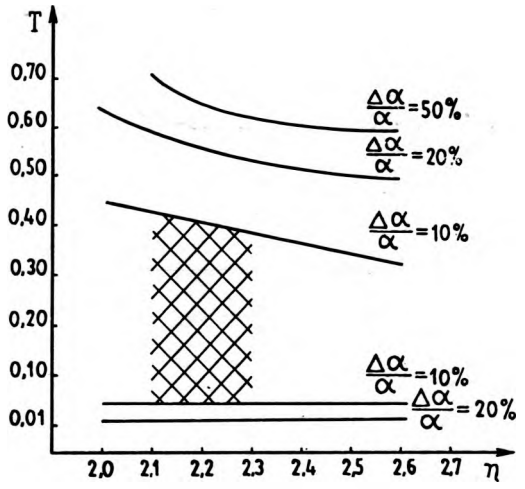

Fig. 4. The relative error ($\Delta a/a^0/_0$) as a function of the transmission T and refractive index n. The calculations were carried out for $\Delta n = 0.1$ and $\Delta T = 0.01$

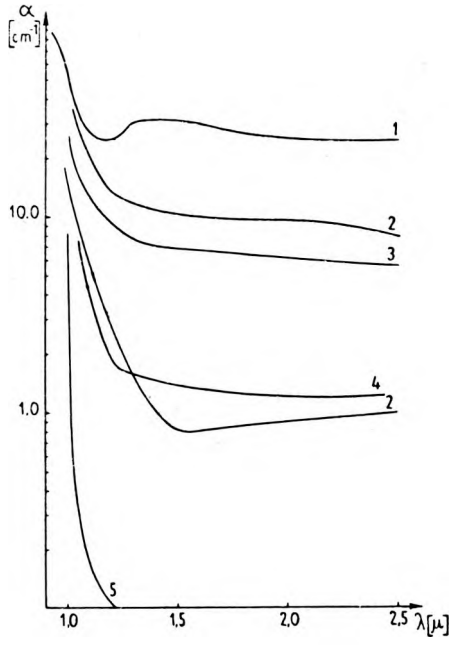

Fig. 5. The results of the absorption measurements taken from papers: 1 – [2], 2 – [4], 3 – [1], 4 – our data (see Fig. 3), 5 – [5]

Absolute values of the absorption coefficients are of order 1–2 cm^{-1} in the spectral region 1.2–2.5 μm (see Fig. 3). The analysis of the accuracy determination of the absorption coefficient from formula (2) was done under assumption that the measured parameters were: transmission T, and refractive index n. The expression for the relative error can be written as

$$\frac{\Delta a}{a} = \left|\frac{\partial a(n, T)}{\partial n}\right| \Delta n + \left|\frac{\partial a(n, T)}{\partial T}\right| \Delta T. \qquad (4)$$

The numerical values of the relative error were calculated for $\Delta n = 0.1$, $\Delta T = 0.01$ in the transmission region from 0.01 to 0.70 and refractive index from 2.0 to 2.6. The results of these calculations are presented graphicaly in Fig. 4.

The curves join points concerning constant error values ($\Delta a/a = 10\ ^0/_0$, $\Delta a/a = 20\ ^0/_0$, $\Delta a/a = 50\ ^0/_0$ respectively).

The region of the greatest accuracy (cross-hatched region in Fig. 4, where $\Delta a/a < 10\ ^0/_0$) is limited by values of the transmission 0.05 and 0.40, at the values 2.1–2.3 of the refractive index. In the region of the transmission greater than 0.60, the relative error is less than $50\ ^0/_0$ (see Fig. 4). The results of the absorption measurements taken from the papers [1], [2], [4], [5] are shown in Fig. 5.

Discussion

As may be seen from the previously mentioned publications [1], [2], [4], [5] and from our results (see Fig. 5) the values of the absorption coefficients differ from each other over two orders of magnitude.

It seems that significant divergences between experimental results may be caused by:

1) Differences in purity of the measured crystals (extremely low values of a can be obtained only with very pure samples).

2) Aplication of the different approximations to calculate the absorption coefficient [2], [5].

3) Different values of the experimental errors (different experimental methods are of different accuracy).

It should be particulary emphasized that the most probable cause of the divergences in experimental results may be conect with the difference in purity of the crystals.

It should be noted that the absorption coefficients in papers [2], [5] were calculated from formula: $T = T_0 10^{-ad}$ (so definited a is called "optic constant attenuation").

Our results and data from the mentioned above papers suggested that the technology of the production of large sufficient purity $Y_3Fe_5O_{12}$ monocrystals is not satisfactorily developed. The scatter in the obtained data may imply difficulties in the concrete technical aplications.

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Оптические сьойства кристалла $Y_3Fe_3O_{12}$ в близкой инфракрасной области спектра

В работе представлены оптические свойства кристалла $Y_3Fe_5O_{12}$ в близкой инфракрасной области спектра.

Проницаемость и показатель преломления определены в диапазоне длины волны от 1 до 2,5 мкм в комнатной температуре. На основании этих данных рассчитан коэффициент поглощения. Полученные результаты сравнены с данными других авторов.

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ERRATA

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56	3 from the bottom	(x,y)-plane	(x,z)-plane
60	5-7 from the top	The error of measurement $\Delta\eta$ was estimated statistically. It turned out that $\Delta\eta \leqslant \pm 0.1$ (relative error $\Delta\eta/\eta$ approx 4.5%).	The error of measurement Δn was estimated statistically. It turned out that $\Delta n \leqslant \pm 0.1$ (relative error $\Delta n/n$ approx 4.5%).