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MODEL OF THE MULTI-WAVELENGTH MAGNETO-OPTICAL ROTATOR

Basiladze G. D., Berzhansky V. N., Dolgov A. I., Prokopov A. R.

Taurida National V. I. Vernadsky University, 4 Vernadsky Ave., Simferopol 95007, Ukraine
E-mail: domain@crimea.edu

The model of a magneto-optical rotator based on a magneto-optical film with the flat conductor of current on its surface is presented. Conductor has a wedge-shaped profile in order to provide simultaneous modulation of the planes of polarization of light beams with identical angular amplitude that have different wavelengths. The formulas for calculation of geometry of a profile of such conductor and of a magnetooptical film depending on the range of working wavelengths and specific Faraday rotation of a film in this range are presented.
Keywords: Faraday rotator, magneto-optical film, the optical switch, optical fiber.

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INTRODUCTION

An important functional component of the light modulators and optical switches based on the Faraday Effect is a device that provides modulation of the plane of polarization of light. It includes magneto-optical (MO) element and a source of a magnetic field magnetizing it. In the known from [1-3] optical switches, as the source of the magnetic field are used inductive coils, in which MO element is located. More attractive for miniaturization and increased performance of the switch is the MO rotator, considered in [4], where the structure in the form of MO film element with the flat conductor with parallel edges coated on its surface [5] is used. The light is introduced into structure through the polished edge of the film and passes in the plane under the conductor perpendicular to the control pulses of current. Polarization of light is modulated at the expense of a planar component of the magnetic field induced by current.

In all mentioned works, the MO rotators in owing spectral dependence of specific Faraday rotation of MO element provided only work on one of wavelengths in telecommunication spectral range. For a possibility of work of MO rotator with several lengths of waves in our work [6] it was offered similar with [4] structure at which unlike analog, the flat conductor on a surface of a film has a wedge-shaped profile.

The aim of this work is to develop a physical model of such MO rotator and receive analytical expressions for calculation of geometry of its elements in dependence of the operating wavelengths of the device and the specific Faraday rotation at these wavelengths for a film that is used.

1. THE PHYSICAL MODEL OF MO ROTATOR AND THE ASSUMPTIONS FOR CALCULATION OF THE PARAMETERS OF ITS ELEMENTS

Fig. 1 is a schematic representation of multi-wavelength MO rotator. The rotator is based on the flat wedge-shaped profile current-carrying element in order to provide identical angle of Faraday rotation of several beams of light with different wavelengths. Beams of light are put in the plane of the film and brought out of it by optical fibers, through respectively, the input and output of the MO film element edges, which are optically polished. While has MO film the magnetic anisotropy of the "easy-plane".

Each of the *N* pairs of input and output fibers, located equidistantly from both sides of MO element operates at its wavelength of light. Moreover, the wavelength λ_N increases with increasing the serial number of the fiber. In other words, is considered the case where at the expense of width of the conductor and, consequently, the length of the light path through the magnetized MO film portion the dependence of specific Faraday rotation from a wavelength of light is compensated [6].

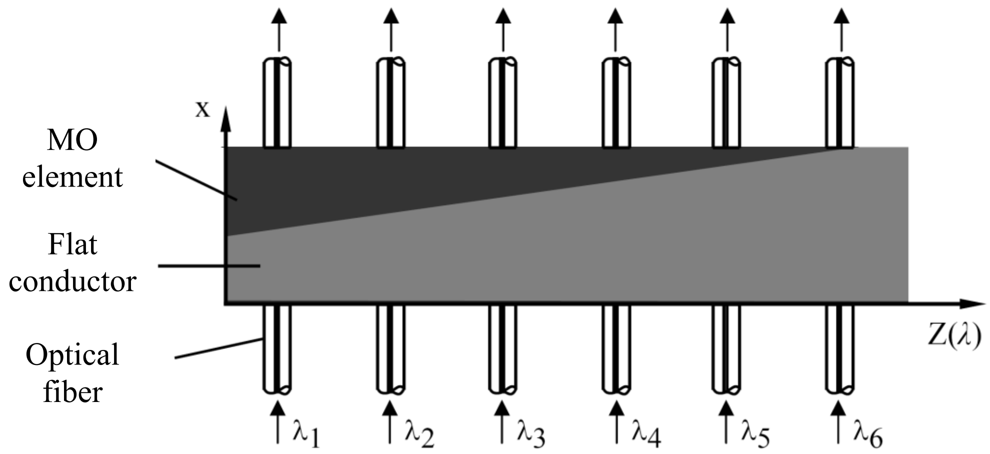
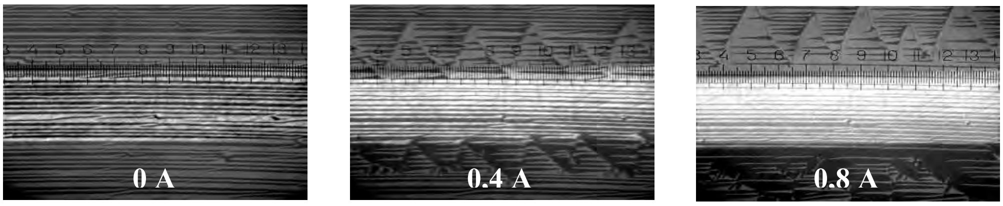


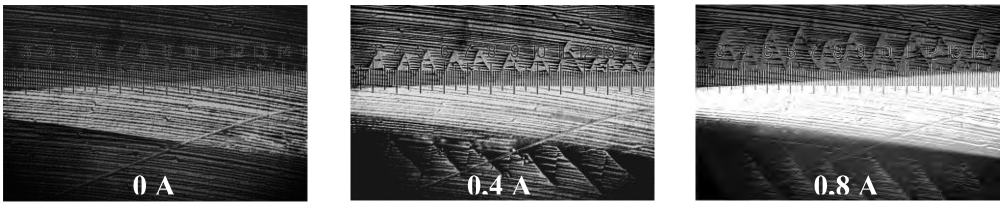
Fig. 1. Schematic representation of the MO rotator with optical fibers for transmitting signals with the corresponding wavelengths.

As it is known at the vast majority of MO materials which are investigated in the literature this coefficient decreases with increase of wavelength. Therefore, we will accept this fact as the first assumption in our calculation.

The second assumption on which the calculation is based relates to the planar component of the magnetic field, which magnetizes MO film in a plane along the light beam, a layer of magneto-optical material under the conductor with current. In this case, it is supposed to use a metal conductor strip width *w* that may exceed the thickness *d* in the amount from several to several tens of times. According to the calculations [7, 8] performed for the planar component of a magnetic field of H_x of the flat conductor with a density of current evenly distributed in cross section, intensity of a planar component of a field has to fall down at the edges of a strip very sharply. Therefore, in the case of relatively low frequency (≤ 1 MHz) pulsed current in our conductor, we assume coincidence of geometric dimensions of the profile of the conductor and the profile of the planar component of the magnetic field under it. As a confirmation of the correctness of this assumption Fig. 2 (a) shows the magneto-optical images copper strips with parallel edges, and, for comparison, Fig. 2 (b) shows copper strips with the edges of wedge-shaped profile obtained by us under identical conditions of giving a direct electric current. In the experiment copper strips of 50 μm thick and about 3 mm wide were used. The wedge strip in narrow portion had a width of about 1 mm. As a magneto-optical indicator was used an epitaxial iron garnet film (EIGF) with a stripe domain structure oriented along the conductor on the surface of which this film was set. Observations were made in a reflected light with the help of the optical microscope. At current inclusion, it is visible, as in the process of its increase more and more domains within contours of both strips are collapsing under the influence of a planar component of a magnetic field. Some non-uniform illumination of images of conductors is explained by uneven contact of a surface of the film with the conductor, and in the case of a wedge-shaped conductor, manifested in the narrow part at the current 0,8 A longitudinal gradient of the current density. The new domain structures observed along the edges of both conductors are reaction of this indicator film on vertical component of a magnetic field. The formation of this type of domains is characteristic for this type of films with small, about 10 Oe, values of the in-plane magnetic anisotropy. As a whole, in the presented photos is obviously expressed the mapping of a planar component of a magnetic field concentrated within borders of profiles of conductors.



a



b

Fig. 2. The magneto-optical images copper strips: a – with parallel edges and b – wedge-shaped profile, with different values of the electric current.

As the third assumption, we consider the dependence of the wavelength of coefficient of Faraday $\theta_F(\lambda)$, as a linear function within near infrared area of a range of 1250-1620 nm, where the MO rotator is planned to use. This assumption is based on the given in [9, 10] dependences $\theta_F(\lambda)$ for a some bismuth-containing garnet materials which within the error of less than 6 % can be approximated by linear functions.

2. CALCULATION OF THE GEOMETRY CURRENT-CARRYING ELEMENT OF THE MO ROTATOR

At first, we obtain an expression for the calculation of the minimum necessary length Z_{min} of the current-carrying element of MO rotator along the current direction. For simplification of reasonings we will accept two conditions which are expedient from the point of view of possibility of a technical embodiment. First, as the minimum acceptable value for δz ($\delta z = Z_N - Z_{N-1}$, see Fig. 3), we take the distance between the axes of two contacting fibers. For example, when using standard (G652) fibers it will make 125 μm. For the reasons of minimization of the sizes of the device it is expediently to bring two beam with closest wavelengths of spectral range through fibers with distance between them equal δz. The second condition is that the interval between any of the predetermined wavelengths has to contain in itself an integer of N of sizes $\delta\lambda$, where N accepts values 1,2,3 … n in ascending order of wave length from the fiber with serial number 1 (Z_1 coordinate in Fig. 3) to the fiber with serial number of n (Z_N coordinate in Fig. 3).

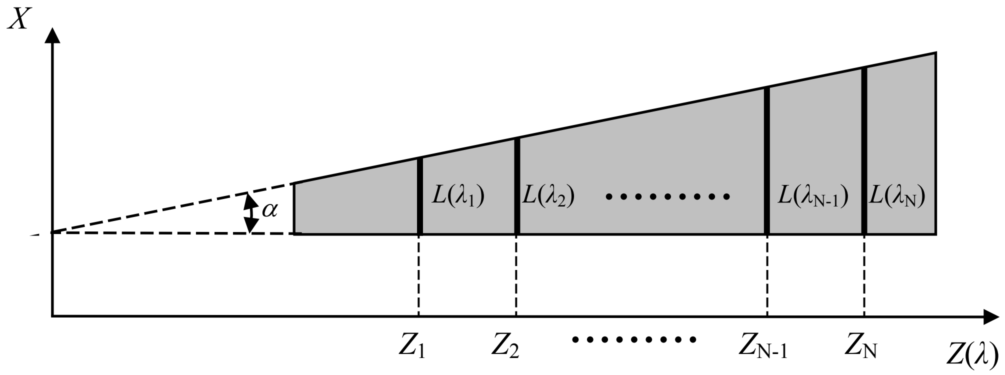


Fig. 3. Model for calculation of the geometry current-carrying element of the MO rotator.

According to these conditions the maximum number of the long-wave channels which can fit in the specified operating range $\Delta\lambda_{work}$ and respectively amount of bringing optical fibers, determined by the expression

$$N_{max} = \Delta\lambda_{work}/\delta\lambda, \tag{1}$$

when $n = N_{max}$ minimum required length of the current-carrying element of the MO rotator Z_{min} and, accordingly, edge of MO element for connecting N_{max} of fibers defined as

$$Z_{min} = N_{max}\cdot\delta z \tag{2}$$

or, through the set long-wave parameters

$$Z_{min} = \delta z\Delta\lambda_{work}\,/\delta\lambda). \tag{3}$$

Further we obtain an expression for the calculation of the longitudinal dimension X or the minimum necessary distance between the edges of the MO element to operate the device, as well as determine the sizes of a wedge-shaped profile of the flat conductor for the rotator.

Let us assume that it is necessary to modulate the light fluxes with wavelengths located in the working spectral range

$$\Delta\lambda_{work} = \lambda_{max} - \lambda_{min}, \quad (4)$$

where λ_{max} and λ_{min} respectively the minimum and maximum wavelengths of this range.

The size of X is determined by the optical path length needed by to rotate the plane of polarization of the light at a predetermined angle Ψ. This length, in accordance with our first assumption, will be the greatest (L_{max}) for the light beam with a maximum wavelength λ_{max}. In turn, the optical path length for the predetermined angle Ψ can be determined through specific Faraday rotation of MO element. Therefore, we can write

$$L_{max} = \Psi/\theta_F(\lambda_{max}), \quad (5)$$

where L_{max} – length of the optical path of the light with the wavelength λ_{max}, needed to rotate the plane of polarized light by a predetermined angle Ψ; $\theta_F(\lambda_{max})$ – specific Faraday rotation of MO element at the maximum wavelength λ_{max}.

Accordingly, the size of X of the MO element in the propagation direction of light can be determined by expression (5), i.e.

$$X = L_{max} = \Psi/\theta_F(\lambda_{max}). \quad (6)$$

Since we have assumed that the length of the interaction of a light beam with the magnetic field determined by conductor width w, then (6) makes it possible to calculate the maximum width of the wedge

$$w_{max} = L_{max} = \Psi/\theta_F(\lambda_{max}). \quad (7)$$

We can similarly calculate the minimum width of the wedge-shaped profile w_{min} by the formula

$$w_{min} = L_{min} = \Psi/\theta_F(\lambda_{min}). \quad (8)$$

Thus, in general, the formula is

$$L(\lambda) = \Psi/\theta_F(\lambda) \quad (9)$$

for the optical path length of light is a key to determine the linear dimensions of the wedge profile $w(\lambda)$ in the direction of propagation of light beams with a predetermined wavelength.

These sizes can be calculated if functional dependence $\theta_F(\lambda)$ of the used magnetooptical material is known. In each of the beams passing though the path $L(\lambda)$, corresponding to its location in the film layer under a wedge-shaped conductor, the plane of polarization has to turn by an angle Ψ when the film is magnetized by the saturation field in the direction of light propagation. As for the function $\theta_F(\lambda)$, then for the calculations in practical purposes it can be determined by the method described in [10], which was applied in research of EIGF for the manufacture of MO elements.

Using (9) and the value of the optical path for light beams with a λ_{max} and λ_{min}, respectively L_{max} and L_{min} needed to determine the formation of the desired wedge-shaped conductor (Fig. 3), we will define a angle α at the vertex of the wedge

$$tg(\alpha) = \frac{L_{\max} - L_{\min}}{Z} = \frac{\dfrac{\psi}{\theta_F(\lambda_{\max})} - \dfrac{\psi}{\theta_F(\lambda_{\min})}}{Z} = \frac{\psi\left[\theta_F(\lambda_{\min}) - \theta_F(\lambda_{\max})\right]}{Z \cdot \theta_F(\lambda_{\max}) \cdot \theta_F(\lambda_{\min})} \quad (10)$$

or

$$\alpha = arctg\left[\frac{\psi\left[\theta_F(\lambda_{\min}) - \theta_F(\lambda_{\max})\right]}{Z \cdot \theta_F(\lambda_{\max}) \cdot \theta_F(\lambda_{\min})}\right]. \quad (11)$$

Value Z on the one hand limited by defined by formulas (2) and (3) minimum permissible length of a wedge-shaped flat conductor $Z_{\min}$, on the other hand, this dimension can be increased. For example, for reasons of manufacturability bond forming of fibers with the end face of the MO element expediently application connecting chips with V-shaped grooves where step of the fibers may be greater than 125 μm. Increase Z and respectively, the step of the fibers may also be caused by a need to reduce gradient of the electric resistance by decreasing the wedge angle at the its apex. That is, the parameter Z in the last formula either is given by the value $Z_{\min}$, or can be set according to requirements of a concrete design of MO rotator.

CONCLUSION

A physical model of MO rotator based on MO film element with the flat conductor of a wedge-shaped profile on a surface of the film was developed. It is assumed that such device will provide simultaneous modulation of the planes of polarization of light beams with different wavelengths with identical angular amplitude.

The model is based on the assumption of the coincidence of the geometric dimensions of the profile of the flat conductor and the planar component of magnetic field beneath. Magnetooptical images of flat conductors with current, which are considered as confirmation of a correctness of such approach, are experimentally received.

The formulas allowing calculation of the plane geometry of the MO element and of the flat conductor of the wedge-shaped profile on its surface, depending on the range of operating wavelengths and the specific Faraday rotation for MO film in this range are obtained.

The received results are planned to be used when designing MO rotator. Such MO rotator, being embedded in a fiber-optical circuit of spectral multiplexers and polarization beam splitters can be used for switching of a multi-wave light flux in fiber-optic communication networks [11].

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References

1. Weng Zihua, Chen Zhimin, Huang Yuanqing, Zhu Yun, Wu Qinping, Wu Dezhi, Yang Guoguang, *Proc. SPIE* **6021**, 725 (2005).
2. R. Bahuguna, M. Mina, J. W. Tioh, R. J. Weber, *IEEE Trans. Magn.* **42**, 3099 (2006).
3. Jianjian Ruan, Zihua Weng, Shaohan Lin, *Proc. SPIE* **7509**, 75090B (2009).
4. Xu Chen, Zihua Weng, Shaohan Lin, Minfeng Wang, *Proc. SPIE* **7134**, 71341Z (2008).

5. S. E. Irvine, A. Y. Elezzabi, *Opt. Commun.* **220,** 325 (2003).
6. G. D. Basiladze, A. I. Dolgov, V. N. Berzhansky, UA Patent No. 70833, Bull. No. 12 (2012).
7. D. Chumakov, High frequency behaviour of magnetic thin film elements for microelectronics, http://www.ifw-dresden.de/userfiles/groups/imw_folder/ publications/theses/Dr_Chumakov.pdf.
8. D. D. Prokof'ev, *Technical Physics* **51**, 675 (2006).
9. Guang-Yu Zhang, Xue-Wu Xu, Tow-Chong Chong, *J. Appl. Phys.* **95**, 5267 (2004).
10. G. D. Basiladze, V. N. Berzhansky, A. I. Dolgov, *Scientific Notes of Taurida National V. I. Vernadsky University, Ser. Physics and Mathematics Sciences* **25 (64)**, No. 1, 160 (2012).
11. G. D. Basiladze, A. I. Dolgov, V. N. Berzhansky, N. A. Fursenko, UA Patent Application No. u201309450, Filed Jul. 29 2013.

Модель багатохвильового магнітооптичного обертача / Г. Д. Басиладзе, В. Н. Бержанський, О І Долгов, А. Р. Прокопов // Вчені записки Таврійського національного університету імені В. І. Вернадського. Серія : Фізико-математичні науки. – 2013. – Т. 26 (65), № 2. – С. 117-124.
Запропоновано модель магнітооптичного обертача на основі магнітооптичної плівки із плоскої електропровідною шиною клиноподібного профілю на її поверхні для забезпечення одночасної модуляції площин поляризації світлових пучків з різними довжинами хвиль із однаковою кутовою амплітудою. Представлено формули для розрахунку геометрії профілю такого провідника і магнітооптичної плівки залежно від діапазону робочих довжин хвиль і питомого фарадеївського обертання плівки в цьому діапазоні.
Ключові слова: фарадеївський обертач, магнітооптична плівка, оптичний перемикач, оптичне волокно.

Модель многоволнового магнитооптического вращателя / Г. Д. Басиладзе, В. Н. Бержанский, А. И. Долгов, А. Р. Прокопов // Ученые записки Таврического национального университета имени В. И. Вернадского. Серия : Физико-математические науки. – 2013. – Т. 26 (65), № 2. – С. 117-124.
Предложена модель магнитооптического вращателя на основе магнитооптической пленки с плоским токонесущим элементом клиновидного профиля на ее поверхности для обеспечения одновременной модуляции плоскостей поляризации световых пучков с разными длинами волн с одинаковой угловой амплитудой. Представлены формулы для расчета геометрии профиля такого проводника и магнитооптической пленки в зависимости от диапазона рабочих длин волн и удельного фарадеевского вращения пленки в этом диапазоне.
Ключевые слова: фарадеевский вращатель, магнитооптическая пленка, оптический переключатель, оптическое волокно.

Список литературы

1. High-speed all-fiber magneto-optic switch and its integration / Weng Zihua, Chen Zhimin, Huang Yuanqing [et al.] // Proc. SPIE. – 2005. – Vol. 6021. – P. 725–736.
2. Magneto–optic–based fiber switch for optical communications / R. Bahuguna, M. Mina, J. W. Tioh, R. J. Weber // IEEE Trans. Magn. – 2006. – Vol. 42, No. 10. – P. 3099–3101.
3. Ruan Jianjian. High-speed magneto-optic switch for optical communication / Jianjian Ruan, Zihua Weng, Shaohan Lin // Proc. of SPIE. – 2009. – Vol. 7509. – P. 75090B-1 – 75090B-9.
4. Analysis and design for ultrafast magneto-optic switch / Xu Chen, Zihua Weng, Shaohan Lin, Minfeng Wang // Proc. of SPIE. – 2008). – Vol. 7134. – P. 71341Z-1 – 71341Z-8.
5. Irvine S. E., Elezzabi A. Y. Wideband magneto-optic modulation in a bismuth-substituted yttrium iron garnet waveguide // Opt. Commun. – 2003. – Vol. 220. – P. 325–329.
6. Патент на полезную модель 70833 Украина, МПК G02F1/01. Магнитооптический вращатель плоскости поляризации света / Г. Д. Басиладзе, А. И. Долгов, В. Н. Бержанский ; ТНУ. – № u201114805 ; заявл. 13.12.2011 ; опубл. 25.06.2012, Бюл. № 12.
7. Chumakov D. High frequency behaviour of magnetic thin film elements for microelectronics [Electronic resource]. – Mode access: http://www.ifw-dresden.de/userfiles/groups/imw_folder/ publications/theses /Dr_Chumakov.pdf, free.
8. Прокофьев Д. Д. Распределение магнитного поля, созданного током, протекающем по пластине, находящейся в сверхпроводящем и нормальном состоянии // ЖТФ. – 2006. – Т. 76, вып. 6. – С. 1–8.

9. Guang-Yu Zhang. Faraday rotation spectra of bismuth-substituted rare-earth iron garnet crystals in optical communication band / Guang-Yu Zhang, Xue-Wu Xu, Tow-Chong Chong // J. Appl. Phys. – 2004. – Vol. 95, No. 10. – P. 5267–5270.
10. Басиладзе Г. Д. Влияние спектральной зависимости коэффициента Фарадея на характеристики излучения, прошедшего планарный магнитоактивный элемент волоконно-оптического переключателя / Г. Д. Басиладзе, В. Н. Бержанский, А. И. Долгов // Ученые записки Таврического национального университета имени В. И. Вернадского. Серия: Физико-математические науки. – 2012. – Т. 25 (64), № 1. – С. 160–169.
11. Заявка на полезную модель № u201309450 Украина, МПК G02F1/09. Магнитооптический вращатель плоскости поляризации света / Г. Д. Басиладзе, А. И. Долгов, В. Н. Бержанский, Н. А. Фурсенко ; ТНУ. – № u201309450 ; заявл. 29.07.2013.

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