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THE POLARIZATION-OPTICAL METHOD FOR SPECTRAL ANALYSIS OF LIGHT

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ПОЛЯРИЗАЦИОННО-ОПТИЧЕСКИЙ МЕТОД СПЕКТРАЛЬНОГО АНАЛИЗА СВЕТА

An analysis of passing the light emission that has Gaussian spectrum through the polarization-optical scheme (POS) with half-wave phase plate has been performed. The results of theoretical calculations of the coherence length of the radiation as a function of the contrast of POS output intensities are obtained for the different widths $\Delta\lambda$ of the Gaussian emission spectrum. The research results of the contrast of POS with $\lambda/2$ phase plate are obtained for the following case: high-power LEDs radiation of red, green and blue spectrum; semiconductor laser red wavelengths; a second harmonic Nd-laser (green wavelength range).

POLARIZE-OPTICAL METHOD, HALF-WAVE PLATE, SPECTRAL ANALYSIS, CONTRAST MODULATION.

В статье представлен спектральный анализ светового потока поляризационно-оптическим методом (ПОМ) с двулучепреломляющей полуволновой пластинкой. Рассмотрены случаи прямоугольного и гауссовского спектра светового потока. Показано, что контрастность ПОМ сильно зависит от ширины спектра света и определяется порядком полуволновой пластинки. Приведены результаты оценки спектра излучения полупроводникового лазера.

ПОЛЯРИЗАЦИОНО-ОПТИЧЕСКИЙ МЕТОД, ПОЛУВОЛНОВАЯ ПЛАСТИНКА, АНАЛИЗ СПЕКТРА, КОНТРАСТНОСТЬ МОДУЛЯЦИИ.

Birefringent (BF) materials are widely used in phase polarization modulation of light. The polarization-optical phase conversion method (POM) of the laser radiation into amplitude modulation is well-known, and it is characterized by high efficiency [1, 2]. This method works in the polarization-optical scheme (POS) (Fig. 1), that consists of the laser *1* with the light of wavelength λ_0 which passes successively through the polarizer *2*, a BF medium *3* of the thickness l and birefringence Δn, the analyzer *4*, and then enters the input photo recording device *5*. In POS, collimated radiation of the source *1* passes through the polarizer *2*, the axis orientation of which is relative to the optical axis of the BF material so that the material transforms the light via BF into two orthogonally polarized light waves of equal intensity. These waves, for various values of the refractive index for the ordinary and extraordinary n_e, n_o waves, acquire different phase delays, depending on the path l of the BF medium. As a result, the output light after the BF material becomes elliptically polarized. At the output after a quarter-wave plate, the light is circularly polarized, while after a half-wave plate the linear polarization is orthogonal to the input polarization. The transformation of this phase-polarization modulation into amplitude modulation is performed by the analyzer *4*. To register this amplitude modulation photo recording device *5* is used (see Fig. 1). The simplest expression of the phase transformation POS into amplitude modulation was obtained for the optimal orientation of the optical axis relative to the axis of the material BF polarizer-analyzer, when modulated radiation had a single wavelength λ_0 [1 – 3]. The maximal variation of light intensity I of the radiation wavelength λ_0 after its passing the polarization-optical scheme with a crossed-polarizer position of the analyzer axes is described by the following expression:

$$I_\perp = I_0 \cdot \sin^2(\pi \Delta n l / \lambda_0),$$

and for the parallel orientation of the polarizer-analyzer axes:

$$I_\parallel = I_0 \cdot \cos^2(\pi \Delta n l / \lambda_0) = I_0 \cos^2(\varphi_0).$$

The transformation of the phase-polarization modulation into amplitude modulation POM for radiation sources with finite spectrum of wavelengths is much more difficult. The present work is devoted to the study of polarization-optical method with a half-wave plate used in the spectral analysis of output light in general case of radiation with a finite continuous spectrum.

The real sources of radiation have a finite frequency range. This results is the fact that the extremes of intensity of light after the POS do not reach their maximum or minimum values. All of this can be used as the basis for POM spectral analysis.

Consider the POS with a half-wave plate with crossed/parallel axes of the polarizer-analyzer. The maximum of normalized change in

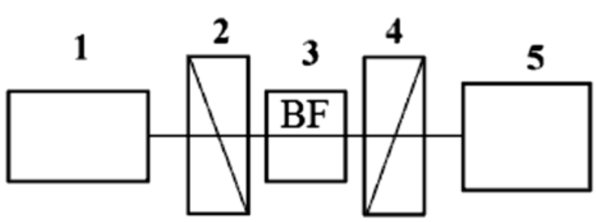

Fig. 1. The polarization-optical scheme (POS)

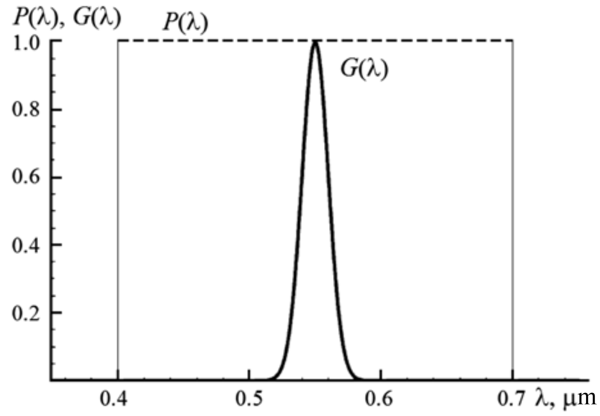

Fig. 2. The rectangular $P(\lambda)$; $\lambda_1 = 0.4$ μm; $\lambda_2 = 0.7$ μm and Gaussian $G(\lambda)$ spectrum. $\lambda_0 = 0.55$ μm, $\sigma = 0.01$ μm

output intensity (1 – 0) or (0 – 1) is taken whenever the orientation of the axes is: polarizer/analyzer: × or ‖, and the phase delay is determined as $\varphi(\lambda_0) = \pi/2$. The maximum depth of the change in intensity is only performed for a specific wavelength λ_0. For the light sources with finite frequency width spectrum of radiation or, in other words, with a finite range of radiated wavelengths: $\Delta\lambda = \lambda_2 - \lambda_1$, the condition of maximum modulation depth is only performed for one wavelength λ_0. For all the other spectral components, this condition is not satisfied, which leads to the reduction of the maximum modulation depth of the radiation.

The amplitude spectral composition of the radiation is described by the spectral density. We will consider two cases of the spectrum: a rectangular spectrum with spectral density $P(\lambda)$ = const, and a Gaussian spectrum with spectral density $G(\lambda)$. LED and laser radiation has a finite frequency spectrum or it has a finite range of wavelengths: $\Delta\lambda = \lambda_2 - \lambda_1$ defining a longitudinal coherence length L_{coh} that for the approximation of a rectangular distribution of the emission spectrum (Fig. 2) can be estimated by the position of the first minimum of the curve of the visibility

$$V = (I_{max} - I_{min})/(I_{max} + I_{min})$$

of the interference pattern: $L_{coh} = \lambda_0^2/\Delta\lambda$. Conditions of POM of extreme values of intensity $I_{min,max}$ ($\varphi = (2N + 1)\pi/2$, where $N = 0, 1, 2, 3, \ldots$ is the wave plate order) are only applied to a specific wavelength of the emission spectrum λ_0, and they are determined by the thickness l and the magnitude of the birefringence Δn_0, while for the rest of the spectral components this condition is not satisfied. The measurement of the width of the spectrum or of the coherence degree is usually conducted by interference methods of the decay curve of the contrast visibility V of the interference pattern in the different interferometers by changing the phase delay of the interfering beams. Such studies of the laser radiation require carrying out the experiment and processing huge amounts of data interferometric patterns obtained in interferometers with a large difference between the variable shoulders. For example, to study LED radiation, there arise certain difficulties due to the small value of the coherence length (10 – 20 μm).

Our method of estimating the width of the spectrum is based on the measurement of the polarization contrast K of the polarization-optical scheme: K is the measurement of the ratio of maximum to minimum output intensity of POS ($K = I_{\times max}/I_{\| min}$ for crossed and parallel polarizer-analyzer axes orientation of POS with half-wave phase plate). The intensity of the radiation transmitted in the polarization-optical system with a parallel orientation of the polarizer-analyzer axes $POS_{\|}$, will have a minimum value. Its value is determined by integrating the spectral radiation density $P(\lambda)$ and $G(\lambda)$ over the entire width of the spectrum and will be proportional to the width of the spectrum: $I_{\| min} \sim \Delta\lambda$ (zero output intensity is reached only for the one wavelength λ_0). Accordingly, the maximum intensity for $POS_{\times}$ with a half-wave phase plate will be achieved for a crossed orientation of the polarizer-analyzer axes. All of this can be used as a basis of a simple method of estimating the light width of the spectrum by means of measuring the contrast $K = I_{\times max}/I_{\| min}$ of POS with a half-wave phase plate.

Consider passing the POS with a half-wave plate by radiation of white light with a rectangular spectral density $P(\lambda)$ with a cutoff wavelength $\lambda_1 = 0.4$ μm, $\lambda_2 = 0.7$ μm and by a narrow-band radiation with a Gaussian spectrum

$$G(\lambda) = e^{-(\lambda-\lambda_0)^2/(2\sigma^2)}$$

with the average wavelength $\lambda_0 = 0.55$ μm and a standard deviation $\sigma = 0.01$ μm (Fig. 2). The density of the radiation spectrum $j_{\times P,G}(\lambda)$ at the output of the polarizer-analyzer with the crossed orientation of the axes $POS_{\times}$ for a rectangular radiation spectrum will be:

$$\begin{cases} j_P = 0, \quad \lambda < 0.4 \ \mu\text{m}; \\ j_{\times P\max} = j_0 \sin^2\left(\dfrac{\pi \cdot \Delta n_0 \cdot l}{\text{л}}\right), \ 0.4 < \lambda < 0.7 \ \mu\text{m}; \\ j_P = 0, \quad \lambda > 0.7 \ \mu\text{m}. \end{cases}$$

For a Gaussian spectrum (Fig. 3):

$$j_{\times G\max} = j_0 \sin^2\left(\frac{\pi \cdot \Delta n_0 \cdot l}{\lambda}\right) \cdot G(\lambda). \qquad (3)$$

The density of the radiation spectrum $j_{\| P,G}(\lambda)$ at the output of the parallel orientation of the polarizer-analyzer axes $POS_{\|}$ for a rectangular radiation spectrum will be:

$$\begin{cases} j_P = 0, \quad \lambda < 0.4 \ \mu\text{m}; \\ j_{\| P\min} = j_0 \cos^2\left(\dfrac{\pi \cdot \Delta n_0 \cdot l}{\lambda}\right), 0.4 < \lambda < 0.7 \ \mu\text{m}; \\ j_P = 0, \quad \lambda > 0.7 \ \mu\text{m}. \end{cases}$$

For a Gaussian spectrum (Fig. 3):

$$j_{\| G\max} = j_0 \cos^2\left(\frac{\pi \cdot \Delta n_0 \cdot l}{\lambda}\right) \cdot G(\lambda). \qquad (4)$$

The output intensity is determined as

$$I_{out} = \int_{\lambda_1}^{\lambda_2} j_{P,G}(\lambda)\, d\lambda. \qquad (5)$$

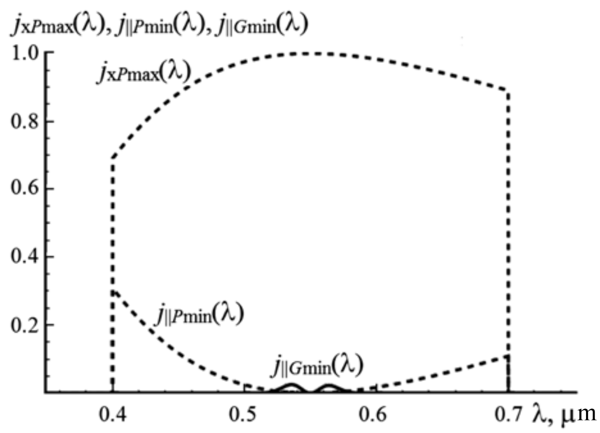

Fig. 3. The density of: the wave with a rectangular spectrum $j_{xP\max}(\lambda)$ after POS_x, the wave with a rectangular spectrum $j_{\| P\max}(\lambda)$ after $POS_{\|}$, the wave with the Gaussian spectrum $j_{\| G\min}(\lambda)$ after POS

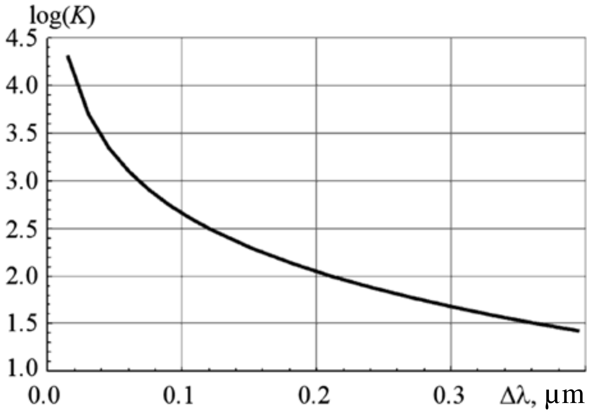

Fig. 4. The logarithm of the contrast intensity POS with zero order half-wave plate from the Gaussian width of the emission spectrum. $\lambda_0 = 0.55$ μm, $\Delta n_0 = 0.04$, $l = 6.88$ μm

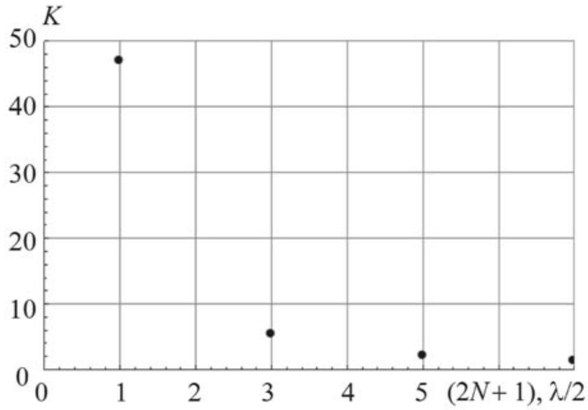

Fig. 5. The dependence of the contrast of the half-wave BF plate from created a path difference of the ordinary and extraordinary waves $\Delta n_0 = 0.04$, the Gaussian spectrum $\lambda_0 = 0.55$ μm, $\sigma = 0.05$ μm

The boundary values of the wavelengths λ_1, λ_2 were determined by the level 0.01 of Gaussian spectrum. The output contrast ratio K of white input light with a rectangular spectrum: $K = 14$, while the contrast of the narrowband modulation in case of Gaussian emission spectrum: $K = 1250$. The modulation depth of white light

$$V = (I_{max} - I_{min})/(I_{max} + I_{min}) = 87\%.$$

Figure 3 shows that the polarization-optical conversion phase modulation into amplitude modulation occurs with the conversion spectrum of the transmitted POS radiation. This is also mentioned in Ref. [4].

The results of theoretical calculations of the logarithm of the contrast intensity POS with zero order half-wave plate from the Gaussian width of the emission spectrum is shown in Fig. 4.

Natural birefringence BF plates, placed in the POS can cause severe transformation of the spectrum of broadband radiation passing POS. Especially clear this phenomenon is for the BF half-wave plates of multiple orders. Zero-order half-wave plates, of the thickness of l_0, creating a path difference $\lambda/2$, a half-wave plate of order N, a thickness of $(2N+1)l_0$, – create a path difference $(2N+1)\lambda/2$. Such plates produce the

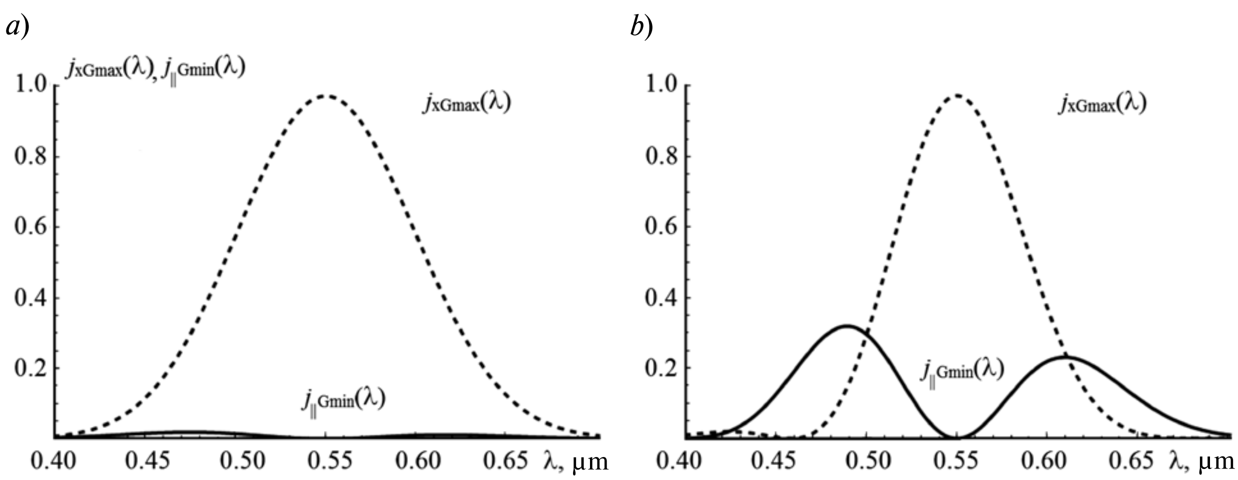

Fig. 6. The spectral density of white Gaussian light spectrum after passing $POS_{x,\|}$ with a half-wave plate: *a* – zero-order ($N = 0$) $\Delta n_0 = 0.04$, thickness $l = 6.88$ μm ($\lambda_0 = 0.55$ μm); *b* – after its passing $POS_{x,\|}$ with a half-wave plate of second order ($N = 2$), $\Delta n_0 = 0.04$, thickness $l = 34.38$ μm

same linear transformation of the input polarization into the orthogonal linearly polarized output radiation. But, the contrast conversion significantly depends on the order of a half-wave plate (Fig. 5). To show this, consider the Gaussian white light emission spectral density

$$G_w(\lambda) = e^{-(\lambda-\lambda_0)^2/(2\sigma^2)}$$

where the average wavelength $\lambda_0 = 0.55$ μm and a standard deviation $\sigma = 0.05$ μm. The spectral density at the output of the POS with a half-wave plate is described by the expression:

$$j^{w}_{\times,\|G} = \frac{G_w(\lambda)}{2}\left(1 \mp \cos\left(\frac{2\pi \cdot \Delta n_0}{\lambda} l\right)\right). \qquad (6)$$

Natural medium birefringence Δn_0 causes severe aperiodic modulation of the spectrum of white light passing the medium-length BF. Fig. 6 *a*, *b* corresponds to $l = 34.38$ μm ($\Delta n_0 = 0.04$). Note that the intensity of the light which has passed POS, in accordance with (5), is being reduced with increasing order of a half-wave plate. The limit value of this reducing is almost 2. About 50 % is lost due to the spectral modulation.

Estimation of radiation spectrum width as a function of the pump current by polarization-optical method was carried out on the example of semiconductor laser HLDPM10-650-1 ($\lambda = 650$ nm). Fig. 7 shows the width of the spectrum decreasing with the increase of the pump current.

It should be noted that our results would correspond to the polarizer-analyzer and the zero order half-wave plate of a high quality only. Usually, a half-wave phase plate, analyzer and polarizer, the quality of workmanship, are far from perfect. These factors can significantly reduce the contrast of the POS with $\lambda/2$ plates. Therefore, the measurement of the width of the emission spectrum of the light source by polarization-optical method with the use of real half-wave plates requires regular calibration by the interference method. The proposed method can be used to quickly estimate the width of the emission spectrum of the light sources.

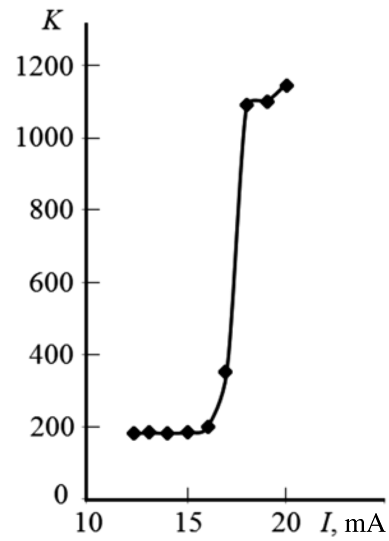

Fig. 7. The dependence of the contrast of the POS with semiconductor laser radiation HLDPM10-650-1 ($\lambda = 650$ nm) in the POS with $\lambda/2$ phase plate on the pump current

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