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DEVELOPMENT OF MULTISPECTRAL RECORDING MEDIA FOR MULTILAYER PHOTOLUMINESCENT INFORMATION RECORDING

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Urgency of the research. Optical information recording by forming of microrelief information elements on the substrate is considered as the most efficient method of long-term data storage.

Target setting. However, density of the optical information recording does not meet the requirements of the modern digital recording systems because diffraction limit significantly reduce the resolution of optical systems.

Actual scientific researches and issues analysis. Scientific research in the area of optical recording shows the high potential of multi-layer photoluminescent media. Volumetric recording is much preferable than development of subdiffraction optical systems due to technical simplicity.

Uninvestigated parts of general matters defining. Typical problems of multilayer photoluminescent recording are low signal-noise ratio and low readout signal level, which makes this method to be inappropriate one for long-term data storage.

The research objective. In this paper it was proposed method of volumetric optical information recording in multilayer, optically homogeneous media with photoluminescent information elements which spectra of photoluminescence differs from layer to layer .

The statement of basic materials. To determine the optimal parameters of multilayer photoluminescent storage with multispectral recording medium the mathematical model of the photoluminescent multilayer recording process was developed.

Conclusions. The task of finding the optimal parameters of the multilayer photoluminescent storage with multispectral recording medium was solved by finding the maximums of the objective functions.

Keywords: optical recording of information; long-term data storage systems; multiispectral medium; photoluminescent multilayer media; readout signal; objective function; function maximum.

Fig .: 7. References: 8.

Urgency of the research. Optical information recording by forming of microrelief information elements on the reflecting substrate and information layers is considered as the most efficient method of non-volatile long-term data storage. It could be indicated by the relevance of work in the field of optical recording of information and long term data storage, as opposed to work in the field of magnetic and solid-state storage which are not considered as archival media.

Target setting. However, density of the optical information recording does not meet the requirements of the modern digital recording systems because diffraction limit significantly reduce the resolution of optical systems. It should be noticed that developers of the modern "Blu-ray" media (BD) has sacrificed the reliability of the optical system. It can be shown that airy disk which determines resolution of the optical system partially overlaps the information elements of adjacent tracks, which leads to the appearance of a parasitic signal.

Actual scientific researches and issues analysis. Basically, there are three ways to solve the diffraction resolution, which can be divided into three groups:

1) optical recording within the diffraction limit [1];
2) development of subdiffraction optical systems [2];
3) development of volumetric optical recording methods [1-6].

In order to increase the optical information recording density within the diffraction limit of optical system it is necessary to achieve a decrease in the laser radiation wavelength λ and an increase in the numerical aperture of the objective NA. It should be noticed that developers of BD have shown the limit on the laser radiation wavelength for the visible range $\lambda = 405$ nm and the $NA = 0.85$ is also close to the limit of the aperture angle. Further decrease of the Airy disk NA could be achieved by the ultraviolet lasers, vacuum systems and technologically sophisticated, superaccurate immersion recording methods which are inappropriable for the mass production and application of the long term storage [1].

Development of the subdiffraction optical systems are also proved to technologically sophisticated, superaccurate immersion recording methods. It was shown that they are significantly reduces the speed of data reading and more suitable for optical microscopy than for information recording [2].

Therefore, high potential of volumetric recording is much preferable than development of subdiffraction optical systems due to technical simplicity [1-6]. The most promising method of volumetric optical recording is the development of optically transparent, homogeneous and anisotropic recording media with multilayer microrelief structures of photoluminescent information elements [1-6].

Uninvestigated parts of general matters defining. It's necessary to notice that main disadvantages of multilayer photoluminescent information recording method leads to the decrease of the reliability of optical media due to low readout signal level associated with the photoluminescent response loss and low signal-noise ratio due to parasitic signal from the multilayer structure [1, 2]. There are different approaches to solve mentioned problems but no uniform methodology for determining the optimal architecture of the optical reading system and storage parameters.

The research objective. In this paper it was proposed method of volumetric optical information recording in multilayer, optically homogeneous media with photoluminescent information elements. Additionally it was propose to develop multispectral recording media for further increase of signal-noise ratio by separating of the photoluminescent signal from different layers. The task of the multilayer photoluminescent storage optimal parameters finding with multispectral recording medium has to be solved by finding the maximums of the objective functions.

The statement of basic materials. To determine the optimal parameters of multilayer photoluminescent storage with multispectral recording medium the mathematical model of the photoluminescent multilayer recording process has to be developed.

The statement of basic materials. Multilayer photoluminescent storage (MPS) includes substrate and sandwich-structure of data layers (DL) and intermediate layers (IL) which should be transparent and optically homogeneus (fig. 1). Thereby further parameters of this media type could be defined:

- geometrical form and linear sizes of layers and substrate;
- data layer thickness d_{DL} ;
- intermediate layers thickness d_{IL} ;
- quantity of the information layers N .

Most important stage of MPS development is determination of the microrelief information structure. Usually developers take as a basis information structure of optical discs (CD, DVD, BD and UMD) that includes information elements (pits) situated in a spiral. Information is coded by pit length and length of the spaces between the pits (lands). Thereby microrelief information structure could be defined by further parameters:

- linear sizes of the pits: set of the pits' lengths $\{l_p^{\min};l_p^{\max}\}$, pits' width w_p and pits' depth d_p ;
- linear sizes of the lands: set of the lands' lengths $\{l_l^{\min};l_l^{\max}\}$, lands' width w_l and lands' depth d_l ;
- track width w_t ;
- refraction coefficient of the layers and substrate n .

MPS readout process implies photoluminescent response, therefore it's important to define recording medium characteristic:

- photoluminescent spectrum (or spectra for multispectral recording);
- absorption spectrum (or spectra for multispectral recording).

And finally should be defined parameters of MPS optical system:

- laser beam wavelength λ ;
- numerical aperture of the objective lens NA ;
- objective lens movement distance h_0 ;
- type of objective lens and diaphragm.

Obviously d_{DL} depends on the on the d_p , while d_{IL} depends on NA and desired value of signal-noise ratio. Thereby d_{IL} must be chosen big enough to divide photoluminescent signal from different layers. While all the structure of the disc is transparent and homogeneous the parasitic signal will be caused mostly by NA and absorption of pits areas lighted by unfocused laser beam. For big enough value of the N parasitic signal will surpass useful signal. It was proposed to distinguish readout signal as a variable one which is possible if pits at the lighted area does not change during readout process.

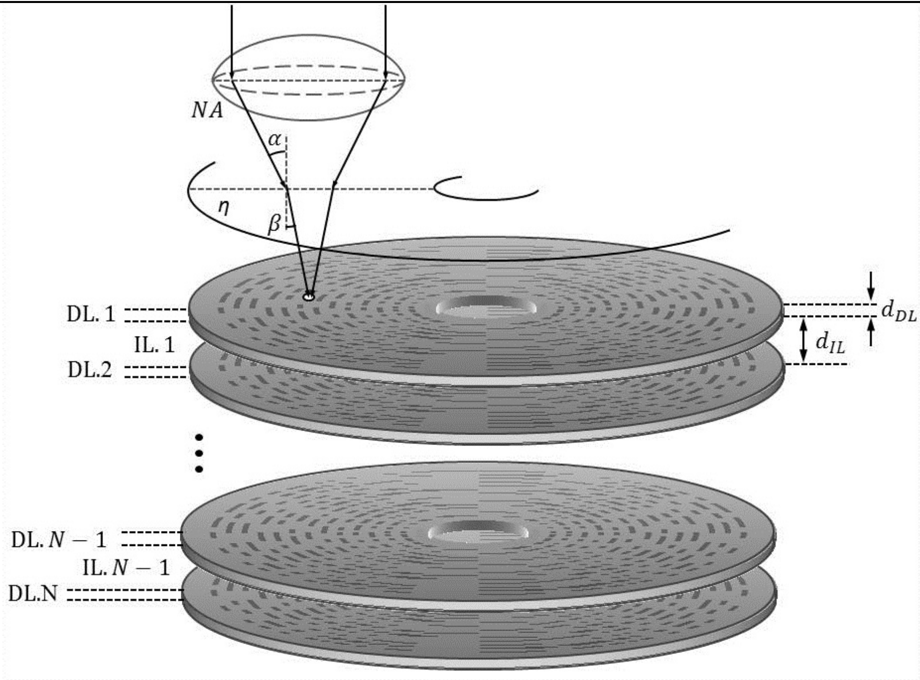


Fig. 1. Structure of the multilayer photoluminescent storage layers.

To avoid undesirable absorption and thereby decrease maximal noise intensity with its variable component it was proposed to record information only by the lands while pits should be recorded by single pulse of laser and can be simulated in mathematical model as cylinders. Furthermore data layer should peripheral area (inner and outside peripheral areas for optical disk structure) which uphold a stable level of parasitic signal during readout from the edges of the disc as its shown at Fig. 2.

While photoluminescent readout signal is spatially isotropic it can be read only part of the probing beam energy within receipt angle $d\Omega$. Finally readout signal power P as a function of probing laser pulse P_0 depends on quantum yield $d\Omega$, absorption factor k_A, receiver system's loss coefficient k_R and out of pit exposure area loss coefficient k_l:

$$P = P_0 \cdot \eta \cdot \left(\frac{d\Omega}{4\pi} \right) \cdot k_A \cdot k_R \cdot k_l \,. \quad (1)$$

Thus the only solving of the low signal-noise ratio is synthesis of the dye with a high photoluminescence quantum yield. It's also important to get luminophor with minimal relaxation time to increase data readout rate.

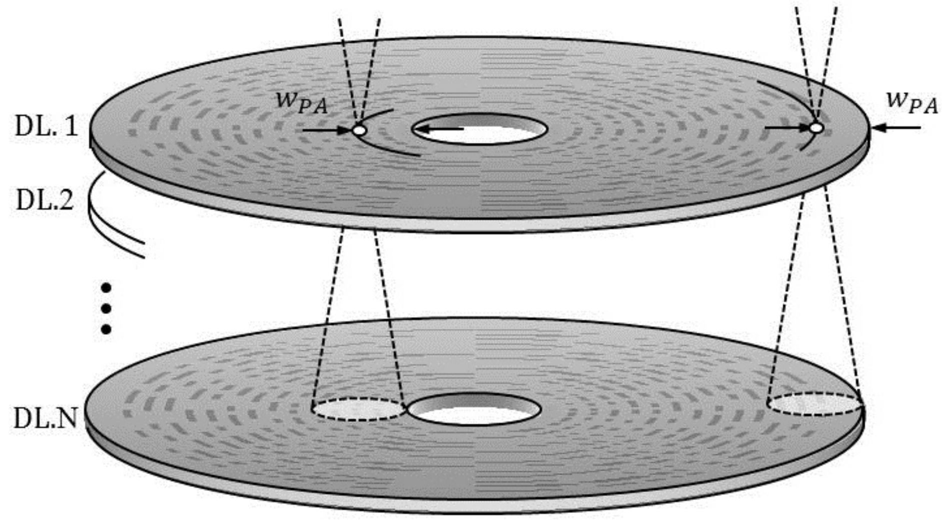


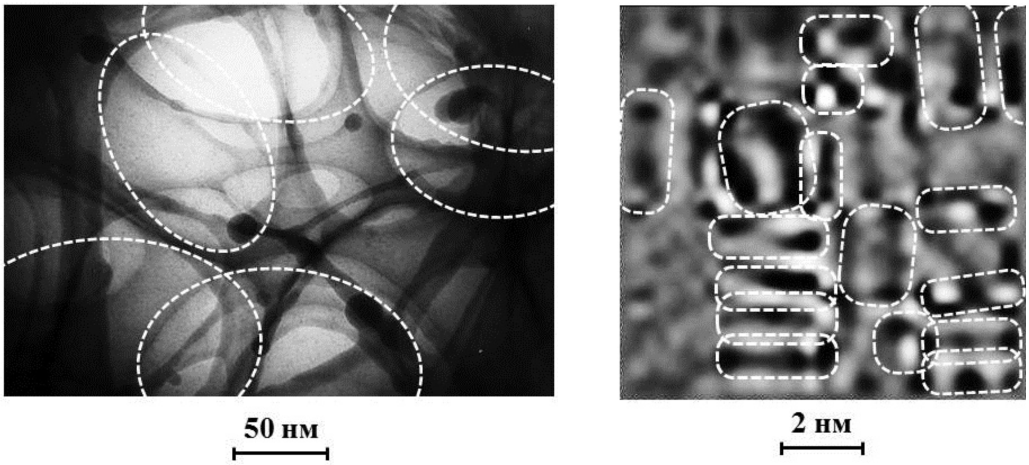
Fig. 2. Determination of inner and outside peripheral areas' width.

There was synthesized class of the pyrazoline dyes which are based on base pyrazoline ultraviolet (UV) dye and pyrazoline "orange-red" with inclusion of polymethylmethacrylate and polystyrene (Table 1). Luminophors were proved to be effective recording media with a quantum yield of photoluminescence value of 60-70%, relaxation time less than 100 ns and wide spectrum of the photoluminescence [1, 2].

Table 1.
Class of the synthesized pyrazoline dyes with inclusion of PMMM and polystyrene [1, 2].

	5% of polymethylmethacrylate	5% of polystyrene
Base pyrazoline ultraviolet dye	53SM	53 SC
Pyrazoline "orange-red" dye	59HM	59HC

Fig. 4 shows for 53SC and 53SM nanostructured pyrazoline dyes that photoluminescence intensity main peak growth could be within 20-30%. Additional laser annealing increases this parameter causing complete inclusion luminophor at nanoscale pores of white zeolite (Table 2). The growth of photoluminescence quantum yield is caused by the quantum size effects which change molecular energy structure of the luminophor. Pyrazolyne luminophor absorption value growth is also concerned with an appearance of the new allowed transitions. In white zeolite porous structure exited molecules relax to the lower levels and thus absorb larger quantities of the laser beam energy. Such effects also cause the rise of additional peaks of the photoluminescence, which was demonstrated for some types of the pyrazoline dyes 53SC and 53SM luminophors. For the structure of complex synthesized pyrazoline dyes is important to consider $\pi\pi^*$ cross-linking with an active energy hydrogen bond. It causes the effect of transmission spectrum infrared shift which was also confirmed by experiment.



(a) (б)

Fig. 3. AFM photographs of pyrazoline luminophor introducing in the white zeolite matrix.

Further research demonstrated potential of the improvement of luminophor parameters by introducing it in the white zeolite matrix [1,2]. The series of experiments confirmed theoretical consideration that zeolite submicron- and nanopores will divide bulk of the dye to the submicron particles (Fig. 3-a: 100-350 nm) and nanoparticles (Fig. 3-b: 1.5-2.5 nm) with a variety of improved optical characteristics.

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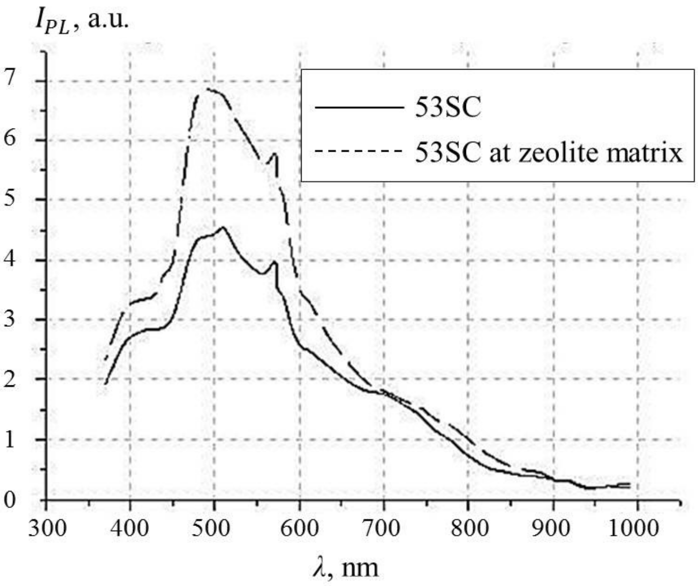
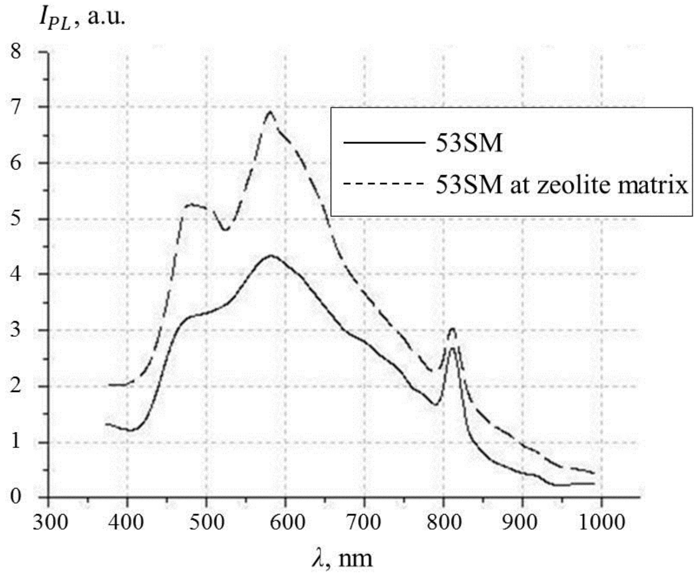
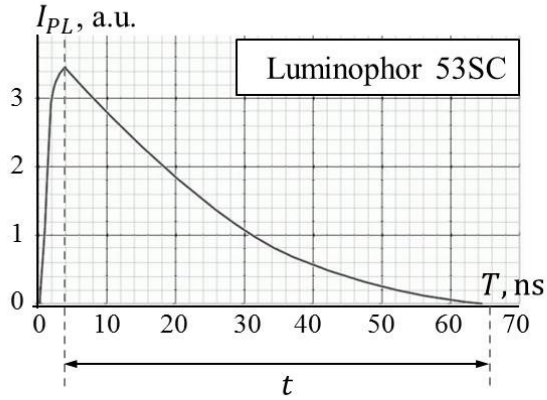


(a)

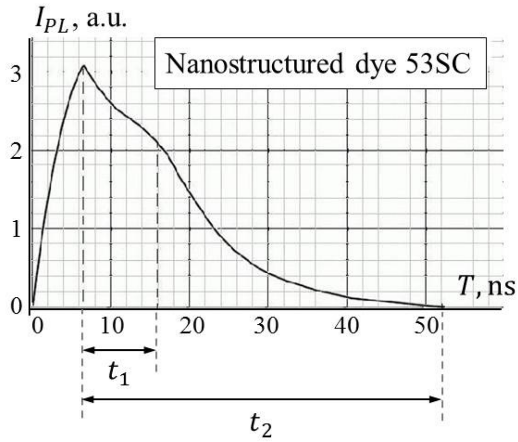


(b)

Fig. 4. Photoluminescent spectra of basic nanostructured pyrazoline luminophors 53SC (a) and 53SM (b) spectra.



(a)



(b)

Fig. 5. Photoluminescent relaxation time of basic (a) nanostructured pyrazoline luminophor 53SC (b) spectra.

To achieve readout rate of MPS close to BD readout system it's necessary to get recording medium with photoluminescence relaxation time lower than 100 ns. Experiments showed that for pyrazoline dyes relaxation time value is within measures t =60…100 ns (Fig. 4-a). Inclusion of the luminophors at the white zeolite matrix allowed to decreas PL photoluminescence relaxation time t =40…60 ns. Application of the complementary laser annealing decreased this value up to t =20…40 ns. Moreover complex structure of the photoluminescense kinetics graph (Fig. 4-b) shows that composite pyrazoline dye has not completely filled nanopores and further annealing will help to get value t =10…20 ns.

Table 2.

Improvement of pyrazoline luminophor parameters by introducing it in the white zeolite matrix

Pyrazoline luminophor	Photoluminescence main peak growth		PL relaxation time decrease	
	before annealing	after annealing	before annealing	after annealing
59HM	19 %	43 %	21 %	47 %
59HC	28 %	47 %	33 %	45 %
53SM	38 %	55 %	36 %	55 %
53SC	45 %	63 %	22 %	29 %

While there are different photoluminescence main peak wavelength but close values of intensity for different luminophors of synthesized dyes class allows to develop multispectral MPS where spectra of photoluminescence differs from layer to layer spectra of photoluminescence differs from layer to layer. It was proposed to analyse possibility of this type of media and optimal parameters of the multispectral MPS by finding the maximums of the objective functions of information capacity and reliability.

Mathematical model was based on simulation of optical media readout system focused laser beam by Gauss function [7, 8]:

$$\begin{cases} I(r,z) = I_0 \left(\dfrac{\omega_0}{\omega(z)} \right)^2 \cdot \exp\left(-\dfrac{2r^2}{\omega^2(z)} \right) \\ \begin{cases} \omega(z) = \omega_0 \cdot \sqrt{1 + \left(1/z_R\right)^2} \\ z_R = \pi\omega_0^2/\lambda \end{cases} \end{cases}, \quad (2)$$

where I is time average function of the electromagnetic field intensity distribution, I_0 is intensity of laser beam at the focus point, ω_0 is the radius of the Airy disk, z is the vertical distance from the focal plane, r is the radial distance from the perpendicular to the focal plane.

At the output data of the mathematical model that simulates the readout process includes:

- I_{SN} as a photoluminescence amplitude of the useful signal during the focusing of the laser beam on the pit (this value summarize useful and parasitic signal);
- I_N as a photoluminescence amplitude of the signal during the focusing of the laser beam on the land (pure parasitic signal);
- $\Delta I_{SN}^{\max}$ as a maximal deviation in the amplitude of the signal when focusing the laser beam on the land (variable part of the parasitic signal).

At the next stage output data was used as indicators and objective functions to define optimal parameters of multispectral MPS:

- k_S is indicator of the useful signal, as the ratio of the useful signal to the maximum possible signal, which occurs when focusing on the pit of the first information layer;

- k_C is contrast indicator as ratio of the useful signal of the averaged photoluminescence signal value received by the readout system;
- k_{SNR} signal-noise ratio as a ratio of the useful signal of a variable component of parasitic signal that cannot be distinguished during readout process.

$$\begin{cases} k_S = \dfrac{I_{SN} - I_N}{I_S^{\max}} \\ k_S = \dfrac{I_{SN} - I_N}{I_{SN}} \\ k_{SNR} = \dfrac{I_{SN}}{\Delta I_{SN}^{\max}} \end{cases} . \quad (3)$$

Defined coefficients allow specifying for multispectral MPS the concept of reliability at the mathematical level (Fig. 5).

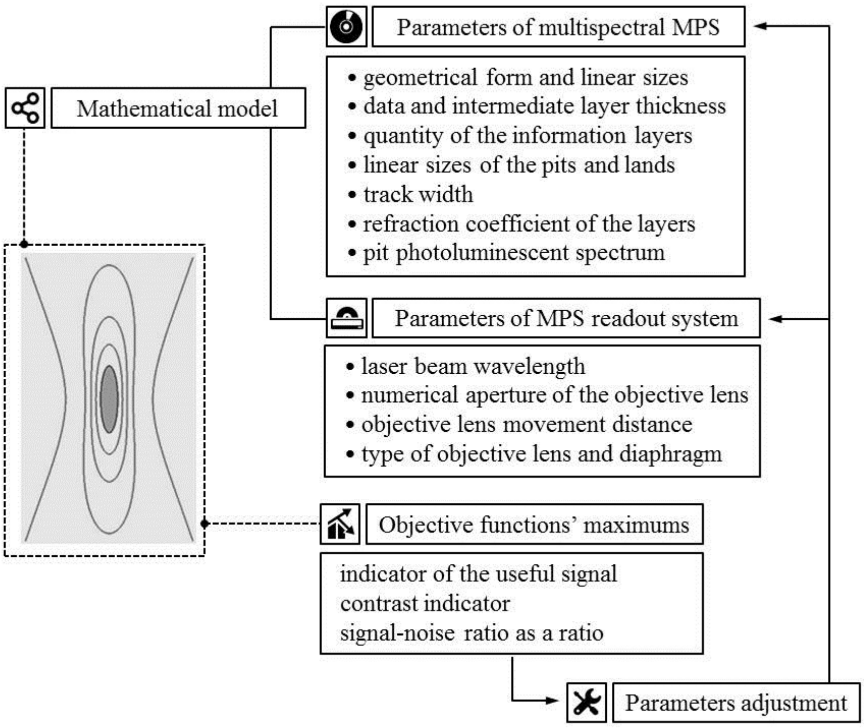


Fig. 6. Algorithm of optimal parameters of the multispectral multilayer photoluminescent storage estimation by finding the maximums of the objective functions.

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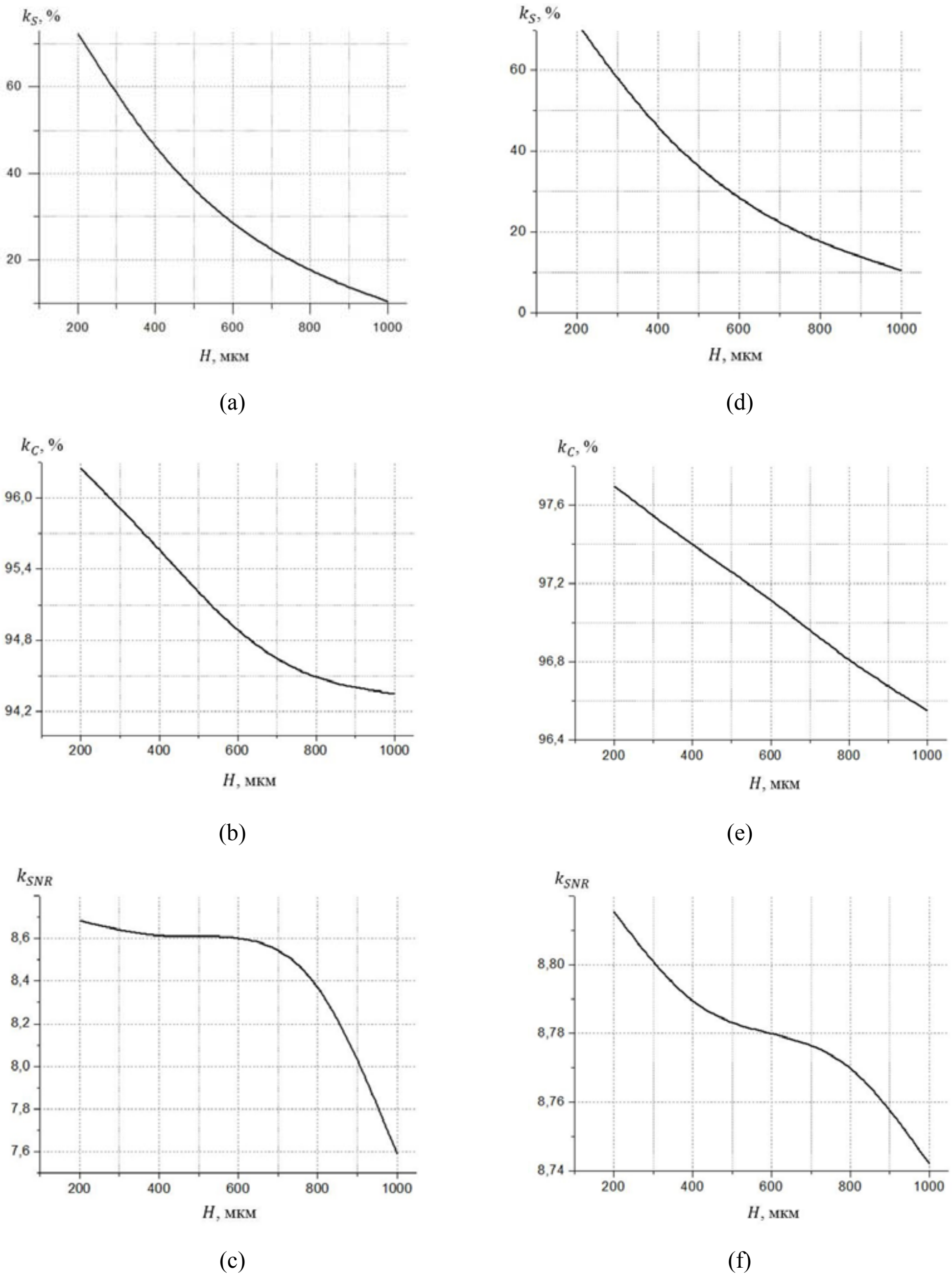

Fig. 7. Indicator function of readout layer depth value for MPS (a, b, c) and multispectral MPS (d, e, f).

At the Fig. 6 shown results of the developed mathematical model of multispectral MPS readout process work for target functions:

- indicator of the useful signal as a function of depth value of readout layer (Fig 1-a for MPS and Fig 1-b for multispectral MPS);
- contrast indicator as a function of depth value of readout layer (Fig 2-a for MPS and Fig 2-b for multispectral MPS);
- signal-noise ratio as a function of depth value of readout layer (Fig 3-a for MPS and Fig 3-b for multispectral MPS).

The results indicate an improvement for $k_C(H)$ and $k_{SNR}(H)$ target functions, while predictably $k_S(H)$ dependence remained unchanged.

Conclusions. To make a proper analysis of multispectral multilayer photoluminescent optimal characteristics it was developed mathematical model and computer simulation of the readout laser beam propagation process. The model included parameters of the storage construction and readout system as input data. Thereby the task of the optimal parameters of the multilayer photoluminescent storage with multispectral recording medium finding was solved by finding the maximums of the objective functions. It was shown that development of multispectral media allows to increase reliability of multilayer photoluminescent media.

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СТВОРЕННЯ МУЛЬТИСПЕКТРАЛЬНИХ РЕЄСТРУВАЛЬНИХ СЕРЕДОВИЩ ДЛЯ БАГАТОШАРОВОГО ФОТОЛЮМІНЕСЦЕНТНОГО ЗАПИСУ ІНФОРМАЦІЇ

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Актуальність теми дослідження. *Оптичний запис інформації шляхом формування мікрорельєфних інформаційних елементів вважається найбільш ефективним способом довготривалого зберігання даних.*

Постановка проблеми. *Однак щільність запису оптичної інформації не відповідає вимогам сучасних цифрових систем запису, оскільки дифракційна межа значно знижує роздільну здатність оптичних систем.*

Аналіз останніх досліджень і публікацій. *Наукові дослідження в області оптичного запису показують високий потенціал багатошарових фотолюмінесцентних середовищ. Об'ємний запис має значні переваги по відношенню до методів розробки субдифракційних оптичних систем у зв'язку з його технічної простотою.*

Виділення недосліджених частин загальної проблеми. *Типовими проблемами багатошарового фотолюмінесцентного запису є низький показник сигнал-шум і низький рівень сигналу зчитування, що робить цей метод неприйнятним для довготривалого зберігання даних.*

Постановка задачі. *У даній роботі був запропонований метод об'ємного оптичного запису інформації в багатошарових, оптично однорідних середовищах з фотолюмінесцентного інформаційними елементами, спектри фотолюмінесценції яких відрізняються від шару до шару.*

Виклад основного матеріалу. *Для визначення оптимальних параметрів багатошарового фотолюмінесцентного зберігання з мультиспектральним реєструваульним середовищем була розроблена математична модель процесу фотолюмінесцентного багатошарового запису.*

Висновки відповідно до статті *Завдання пошуку оптимальних параметрів багатошарового фотолюмінесцентного сховища з мультиспектральним реєструвальним середовищем була зведена до задачі знаходження максимумів цільових функцій.*

Ключові слова: *оптичний запис інформації; системи довгострокового зберігання даних; мультиспектральне реєструвальне середовище; багатошаровий фотолюмінесцентного носій інформації; сигнал зчитування; цільова функція; максимум функції.*

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