Organization of optical systems for multilevel volume recording for long-term storage of large data arrays

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Abstract
A methodology for designing optical systems with multilevel volumetric recording for long-term data storage is proposed. A new recording medium based on pyrazoline luminophores with high photostability and efficient luminescence was synthesized. The structure of the data carrier was optimized to increase recording density and ensure stable readout. A direct laser writing method was applied to achieve high-precision microrelief formation.

Keywords
multilevel optical recording, volumetric data storage, pyrazoline luminophores, direct laser writing

1. Introduction

The rapid growth in the volume of digital information over recent decades (particularly the trend of data volume doubling approximately every two years over the past twenty years) has created an urgent demand for the development of reliable long-term data storage systems capable of preserving large-scale datasets with the potential for further scalability [1, 2]. Among existing technologies, optical data carriers are distinguished by their high stability and long-term storage potential, which is achieved through the formation of microrelief structures on monocrystalline substrates. To increase the storage capacity of such carriers, the implementation of multilevel and multilayer optical recording approaches has become especially relevant. These approaches, however, require the development of new functional materials, optimization of the internal structure of information layers, and enhancement of laser recording systems. For conventional optical discs, the implementation of multilayer and multilevel recording approaches cannot be achieved in an explicit or straightforward manner due to inherent technological constraints, primarily related to the limited number of feasible information layers and discrete encoding levels, which arise from optical cross-talk, signal attenuation, and the structural limitations of reflective layer-based architectures. Within this study, a methodology for organizing an optical system was developed to ensure long-term data preservation with high precision and reliability.

2. Conceptual framework for multilayer photoluminescent media organization

As previously noted, one of the most straightforward approaches to overcoming the problem of low optical capacity in traditional optical discs without introducing significant changes to the data-

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reading drive architecture or the physical structure of the storage medium is the concept of multilayer optical recording. An optical disc comprising *N* information layers enables the exploitation of the advantages inherent in volumetric data storage, whereby, under the condition of maintaining the original surface recording density, the total storage capacity of the medium can be theoretically scaled by a factor of *N*. However, in conventional optical discs, where each data layer is coated with a reflective material, the multilayer recording method encounters substantial limitations. The primary drawback is that in such reflective multilayer structures, the probing laser beam undergoes multiple reflections and partial absorption, leading to an exponential-like degradation in the signal-to-noise ratio (SNR). To address this issue, researchers propose the use of optically homogeneous media, in which data elements (pits) may act as reflective structures, absorptive regions, phase-shifting elements, or photoluminescent emitters under laser excitation. Particular emphasis is placed on the development of a multilayer photoluminescent disc (PMD).

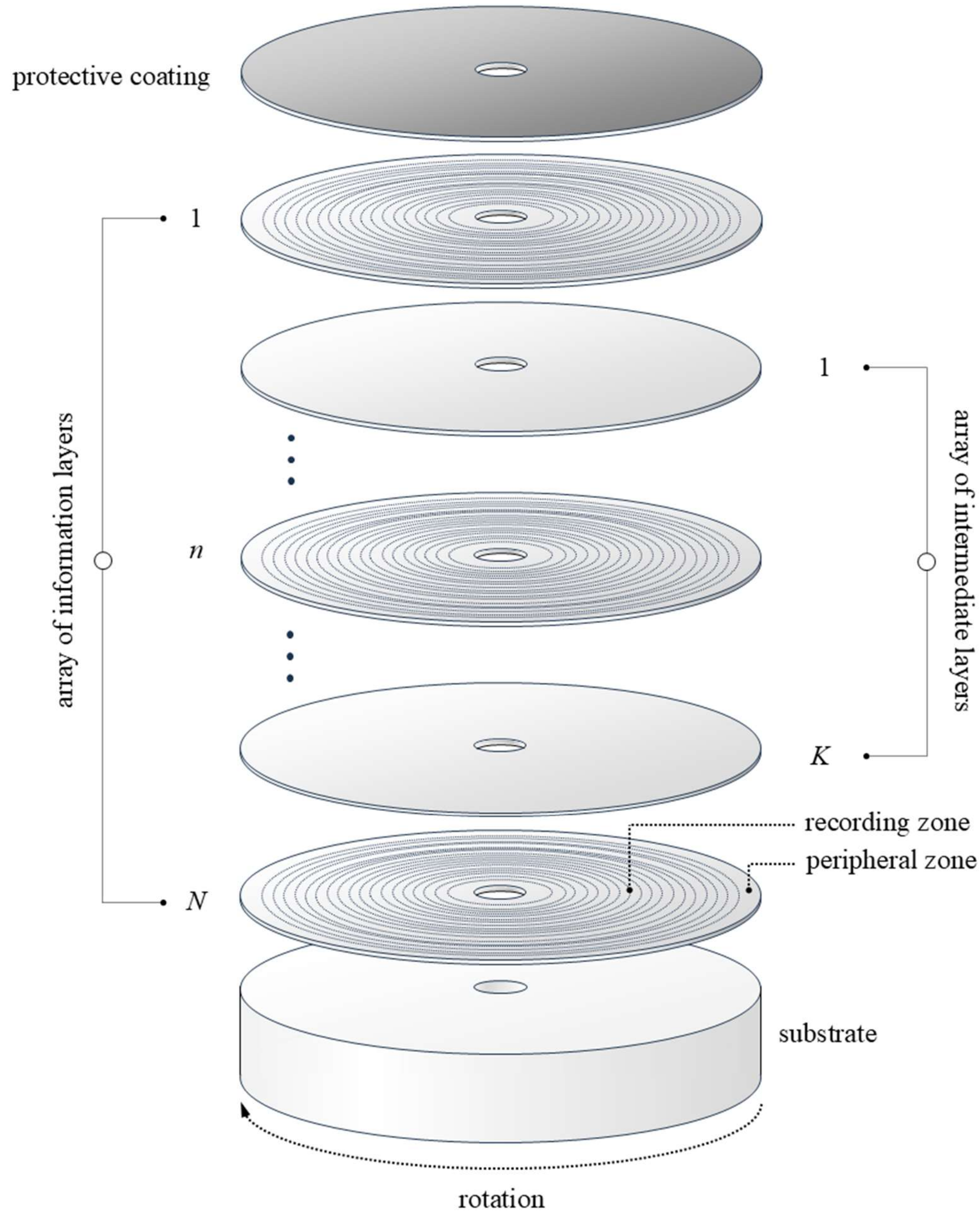


Figure 1: Basic diagram of the structural organization of a multilayer photoluminescent disc

The key advantage of photoluminescent data registration in multilayer configurations lies in the wavelength shift between the excitation and the emitted photoluminescent signal, known as the Stokes shift, typically into the shorter-wavelength spectral region [2]. This spectral separation effectively eliminates the primary source of interlayer crosstalk (namely, multiple internal reflections) rendering the SNR far less dependent on the number of layers N. Consequently, researchers can focus their efforts primarily on minimizing interference from residual signals generated by adjacent, non-target layers that are unintentionally excited during the readout process from the PMD medium. Within the framework of constructing a mathematical model, it is proposed to consider a PMD composed of a sandwich-like structure consisting of N information layers, separated by $K = N - 1$ intermediate layers, in addition to a substrate and a protective coating (Figure 1). The size and proportions of the PMD's structural components are determined by the characteristics of the optical system, in particular by the objective lens numerical aperture and the wavelength of the laser beam used for writing and reading processes. The primary performance indicators of the optical recording system are the overall information capacity of the PMD and the reliability of useful signal reproduction during the readout process, both of which are directly influenced by the spatial resolution and spectral characteristics of the system. The parasitic signal arises from the fact that, under conditions of single-photon photoluminescent readout, all information layers are simultaneously irradiated and consequently contribute to the overall photoluminescent response, rather than solely the layer on which the laser beam is focused. If the separating layers are made thick enough, large portions of the neighboring data planes, including many recorded pits, become affected by the excitation beam and produce unwanted background luminescence. The mean level of this parasitic signal scales with the ratio of pit-covered area to the overall illuminated region. To mitigate the problem, the readout regime can be arranged so that the background contribution remains practically constant for all layers, which makes the retrieval of the useful signal more stable.

However, as more detailed analysis reveals, the total parasitic signal, even under conditions where the intermediate layers possess sufficient thickness, does not remain constant in the general case. The primary reason lies in the variation of irradiation intensity across the lower-lying information layers, which depends on whether the laser beam is focused on a photoluminescent pit or on a land within the active reading layer. To enhance the SNR of the PMD, a recording strategy has been proposed in which information is encoded exclusively through variations in land length. Reading data from areas close to the inner or outer margins of a layer's recording zone is problematic, since in such positions the laser spot may partly illuminate regions outside the valid recording field on adjacent layers, reducing the accuracy of signal discrimination. This results in a decrease in the intensity of the parasitic photoluminescent signal, leading to its deviation from the previously assumed constant value and, consequently, to erroneous extraction of the useful signal by the readout system. To compensate for this effect, it has been proposed to introduce peripheral inner and outer zones on each information layer, within which tracks structurally identical to information tracks are formed but which do not carry useful data. Instead, these zones are designed to emit a photoluminescent signal equivalent in intensity to that of the corresponding active data regions. Calculations have shown that, when selecting the geometric dimensions of the PMD in accordance with the standard optical disc format and under the condition of using a high numerical aperture objective lens, the total area of these peripheral zones depends on the optical parameters of the readout system and does not exceed 1.8% of the total area of the information layer recording zone.

3. Mathematical modeling of data retrieval from a multilayer photoluminescent disc

Given that the medium of the photoluminescent disk is optically homogeneous, and the effects of partial transparency and diffraction at the edges of the recorded relief structures can be reasonably neglected, the overall complexity of the modeling task is significantly reduced. As a result, the focus shifts primarily to the development of appropriate software capable of simulating and optimizing the system's parameters. The developed simulation framework makes it possible to select optimal parameters of the system, such as pit depth, thickness of both data-bearing and separating layers, overall geometry of the carrier, transmission properties of the recording medium, numerical aperture of the lens, and the detection threshold of the readout head. Notably, the optimization procedure may result in several alternative solutions (both local and global) that provide high values of signal-to-noise ratio, stable readout amplitude, and increased storage capacity. This multiplicity of viable solutions is especially advantageous when designing and implementing volumetric photoluminescent recording systems, as it allows for flexibility in adapting the optical architecture to varying material constraints, operational conditions, and target application requirements [2-4].

To build the mathematical model, the starting point is the expression for a focused laser beam, in which the spatial distribution of the electric field across the beam cross-section is described by a Gaussian approximation. This is expressed through the time-averaged intensity distribution function $\bar{I}(r,z)$, defined as the ratio of the electric field amplitude $E(r,z)$ to the wave impedance η:

$$\bar{I}(r,z) = \left(E(r,z)\right)^2/2\eta = I_0 \cdot (\omega_0/\omega(z))^2 \cdot e^{-2(r/\omega(z))^2}, \tag{1}$$

where I_0 is the beam intensity at the focus $\bar{I}(0,0)$, ω_0 is the Airy disk radius, z is the axial (vertical) distance from the focal plane, and r is the radial distance from the optical axis perpendicular to the focal plane. In this case, $\omega(z)$ is calculated as:

$$\omega(z) = \omega_0 \cdot \sqrt{1 + (z/(\pi \cdot \omega_0^2/\lambda))^2}, \tag{2}$$

where λ is beam wavelength.

After the initial formulation, the mathematical model was further refined to integrate the specific optical properties of the recording system. In particular, it was adjusted to reflect the influence of the objective lens parameters, including its numerical aperture, focal distance, and aberration profile, as well as other system-dependent characteristics that affect beam focusing and signal formation. With these refinements, the task of defining the physical and geometrical parameters of the PMD could no longer be treated as a simple calculation of individual variables. Instead, it was systematically reformulated as a mathematical optimization problem, where multiple interdependent criteria had to be simultaneously satisfied. Specifically, it was reduced to the problem of identifying the maxima and minima of several target functions, each corresponding to key performance indicators such as signal strength, signal-to-noise ratio, data layer resolution, and overall storage capacity. This reformulation enables the application of established optimization techniques and numerical methods to systematically explore the design space and determine configurations that offer optimal recording and readout performance under given physical and technological constraints. The following parameters of the optical readout system were used as target functions in the optimization process:

1. The overall storage capacity of the medium, calculated as the multiplication of the information volume that can be held by a single recording layer and the total number of layers incorporated into the photoluminescent disk.
2. Data retrieval reliability, which is determined by multiple contributing factors, including signal contrast, SNR and stability of signal reproduction under varying optical and material conditions.
3. Amplitude of the useful signal at the output of the optical detection system, which directly affects the ability to distinguish data features from background noise;

4. Sensitivity of the readout system to errors arising during the formation of the data layer, such as variations in thickness, refractive index mismatches, or structural inconsistencies that may reduce fidelity.
5. Sensitivity to errors during the formation of individual data elements (pits or voxels), which can result from limitations in spatial resolution, recording beam stability, or material response uniformity.

These target functions depend on a set of physical and optical design variables, which served as arguments in the optimization problem:

- linear dimensions of the data element, including pit diameter and depth, which influence both the achievable data density and the optical resolution required for reliable readout;
- thickness of the intermediate layer between successive data layers, which affects interlayer crosstalk and the axial resolution of the optical system;
- absorption coefficient of the data element, which determines the level of signal attenuation and contrast in the readout process;
- photoluminescent efficiency (quantum yield) of the data element, which affects the intensity and quality of the emitted signal;
- refractive indices of the substrate, data layer, and intermediate layers, which influence beam focusing, reflection, and transmission within the multilayer optical stack;
- wavelength of the probe readout beam, which determines the diffraction-limited resolution and interaction depth in the medium;
- numerical aperture of the optical readout system, a critical factor that governs the spatial resolution, focusing capability, and light-gathering efficiency of the lens system.

Based on the developed mathematical model, an in-depth analysis was conducted of the intensity distribution function of a focused laser beam in the context of optical systems used in conventional optical disk drives. The simulation results revealed significant advantages of employing high numerical aperture optical systems in the context of volumetric optical data recording. These advantages include improved spatial resolution, higher signal contrast, and increased capacity for precise energy localization within the recording medium. Considering the specific properties of PMD-type media, the surface relief of the data layer should be aligned with the isoline that corresponds to the $1/e^2$ level of the maximum beam intensity. Such an approach guarantees that the laser energy is concentrated within the most effective region of the focal spot, thereby enhancing excitation efficiency of the recording material. As a result, the actual depth of the pits in the PMD is not arbitrary, but rather determined by two principal optical parameters: the emission wavelength of the laser and the numerical aperture of the focusing lens. The variation of these parameters directly influences the achievable axial resolution and the effective depth of field within the multilayer medium. Through comparative evaluation, it was determined that the optimal configuration of an optical storage device based on PMD technology closely resembles the optical architecture of Blu-ray disc systems. Such systems are characterized by short-wavelength lasers ($\lambda = 405$ nm) and high numerical aperture lenses ($NA = 0.85$), which collectively provide a favorable balance between resolution, recording depth, and signal stability in multilayer photoluminescent recording environments.

4. Synthesis of the recording medium based on a nanostructured pyrazoline luminophore

In order to develop a photoluminescent recording medium for PMD, a series of organic pyrazoline-based dyes were synthesized. The synthesis of an orange-red dye, specifically 4-[1,5-diphenyl-2-pyrazolinyl-3]-n-phenylnaphthalimide, was carried out following a synthetic pathway proposed in, with a modification introduced at the condensation stage: aniline was used in place of o-phenylenediamide in the reaction with acetylnaphthalic acid. Thin films of the synthesized dyes were prepared by spin-coating appropriate solutions onto glass substrates using a centrifuge. The resulting films had an average thickness of approximately 1 μm. The dye solutions were prepared according to the following procedure: (a) pyrazoline dyes were dissolved in toluene; (b) the resulting solutions were introduced into polymer matrices based on polymethyl methacrylate (PMMA) or polystyrene, with the polymer additive constituting 5% by weight relative to the dye component. For convenience in spectroscopic identification, the photoluminescence spectra of the obtained dyes were labeled as follows: HM — the orange-red dye embedded in a PMMA matrix; HC — the same dye embedded in a polystyrene matrix. In addition, a portion of the dye samples was dissolved in Rengolux UV-resistant lacquer, a material commonly used for the protective coating of compact discs against ultraviolet (UV) radiation. The photoluminescence spectra in the $\lambda = 380 - 1100$ nm range were recorded using an automated diffraction spectrometer. Excitation of photoluminescence was performed using a nitrogen laser ($\lambda = 337$ nm). The relaxation dynamics of the dye molecular complexes were studied by measuring the decay kinetics of photoluminescent signals excited by $\Delta t_{\mathrm{UV}} = 10$ ns laser pulses from the nitrogen laser. Photoluminescent decay curves of luminophore medium were recorded using a photomultiplier tube in combination with oscilloscope, offering a temporal resolution of $\Delta t_{\mathrm{PH}} = 5$ ns 5 ns.

It was noted that the submicron-scale structure of the PMD recording medium may give rise to quantum-size effects within the photoluminescent recording environment. To investigate this hypothesis, a series of experiments was conducted in which pyrazoline-based dyes were incorporated into a white zeolite matrix, known for its submicron and nanometer-scale pores. Zeolites, due to their nanoporous architecture, provide a confined environment that can lead to spatial quantization of electronic states, potentially affecting the photophysical properties of the embedded luminophores. Experimental analysis revealed that the pyrazoline dyes exhibited several key characteristics making them highly suitable for use in volumetric optical recording systems:

1. High photoluminescence quantum yield of 60-75%, which is particularly beneficial for reading isotropic PL signals with sufficient signal intensity;
2. Short photoluminescence relaxation time $t = 60 - 100$ ns, enabling data readout speeds comparable to those achieved with conventional reflective optical disks;
3. Tunable emission spectra, made possible by the controlled introduction of dopants or modifying the local chemical environment within the matrix;
4. Strong absorption in the short-wavelength region of the optical spectrum, facilitating efficient excitation with UV or violet laser sources;
5. Adequate photosensitivity for local bleaching-based data recording, driven by thermally induced dye degradation under focused laser exposure;
6. Large Stokes shift $\Delta\lambda = 250 - 480$ nm, which ensures effective separation between the emitted PL signal and the reflection signal originating from the disk surface, thus improving signal detection and contrast during readout.

These results suggest that the integration of pyrazoline luminophores into nanostructured host matrices offers a promising pathway for enhancing the performance and efficiency of photoluminescent multilayer optical storage technologies.

Quantum-chemical calculations of the electronic spectra of this class of dyes indicate that their photoluminescent behavior is primarily governed by a strong $\pi \to \pi^*$ electronic transition. In this process, excitation involves the promotion of a π-electron to an excited π^* orbital, with a high oscillator strength, which accounts for the intense photoluminescence observed. It should be emphasized that σ-electrons have no direct role in generating the emission observed in the visible part of the photoluminescent spectrum, since the photon energies corresponding to $\sigma \to \sigma^*$ electronic transitions are located far in the ultraviolet region. The wide emission profile typical of such luminophores arises because the radiative decay proceeds from the lowest vibrational sublevels of the excited electronic state toward a continuum of vibrational states in the ground electronic manifold. Consequently, the emission spectrum is broadened rather than confined to a narrow line.

Furthermore, the exact location of the photoluminescence maximum is strongly dependent on intermolecular interactions and the characteristics of the host matrix. Such intermolecular interactions can induce shifts in energy levels and alter emission characteristics. Furthermore, the magnitude of the Stokes shift is largely determined by electron–phonon interactions within the dye–matrix adsorption complex. In this configuration, the dye molecule is surrounded by the matrix constituents, which modify its electronic environment through local field effects and vibrational coupling.

Experimental observations confirm that the interaction between pyrazoline dye molecules and PMMA is significantly stronger than that with polystyrene. This stronger interaction in PMMA matrices results in more pronounced shifts in emission spectra and greater stabilization of excited states, which are critical for the stability and efficiency of the photoluminescent response in optical recording applications. The incorporation of pyrazoline dyes into a zeolite matrix (effectively breaking down the monolithic luminophore into nanoscale particles) resulted in the partial relaxation of certain otherwise forbidden electronic transitions within the dye structure. This nanostructuring effect is attributed to spatial confinement and perturbations in the molecular symmetry of the dye molecules embedded in the porous zeolite framework. The experimental observations confirmed that the introduced structural adjustment produced a clear enhancement of the main photoluminescence peak intensity and simultaneously shortened the relaxation time of the luminescent response. These enhancements are particularly advantageous for high-speed optical readout applications, where both signal strength and temporal resolution are critical. Further improvement in the performance of the recording medium was achieved through laser annealing in the infrared (IR) range. This thermal treatment facilitated deeper penetration of the dye molecules into the smaller pores of the zeolite, promoting more uniform distribution at the nanoscale. In the context of constructing PMD, such processing translates into an information layer with higher surface recording density and, consequently, smaller individual data elements. However, it was also observed that when higher laser intensities were used during the annealing process, partial bleaching of the dye occurred due to thermal degradation. This effect imposes a limitation on the maximum permissible energy input during post-deposition processing and underscores the need for precise control of laser exposure parameters to balance structural optimization with dye stability.

As the basis for the PMD recording medium, a nanostructured orange-red pyrazoline dye embedded in PMMA matrix was selected. Following laser annealing, this material demonstrated superior performance across all key evaluation criteria. Specifically, it exhibited enhanced photoluminescence intensity, reduced relaxation time, improved spatial uniformity of the photoluminescent layer, contributing to more precise data localization and reduced signal distortion, high thermal and photostability, critical for long-term data retention and repeated readout cycles, pronounced Stokes shift, strong interaction with the PMMA matrix, which ensured stable dye immobilization and limited dye aggregation or migration over time.

5. Numerical simulation of readout performance in photoluminescent multilayer media

In the present stage of the study, the simulation of the optical readout process was performed with a spatial resolution of 100 nm. This discretization step was chosen to ensure sufficient accuracy in describing the beam profile and its interaction with individual layers of the PMD. The adopted resolution allowed for tracing the propagation of the probing beam through the multilayer structure in detail, taking into account the effects of refraction, scattering, and partial absorption within the intermediate and active layers. The model incorporated both the physical characteristics of the nanostructured orange-red pyrazoline dye embedded in PMMA matrix and the optical parameters of the PMD drive system. From the modeling procedure, the key outcome parameters can be summarized as follows:

- amplitude of the photoluminescent response under pit-focused excitation, which includes both the useful contribution and the background (parasitic) component.
- maximum fluctuation in the PL amplitude at the pit location, characterizing the degree of variability or instability in the recorded signal.
- photoluminescent signal amplitude when the probing beam is focused on a land area, representing the parasitic background signal;
- maximum amplitude deviation of the photoluminescence signal when focused on a land, which characterizes fluctuations in the background signal level.

The raw output data were further processed and transformed into a set of normalized performance indicators for quantitative assessment of the optical readout system:

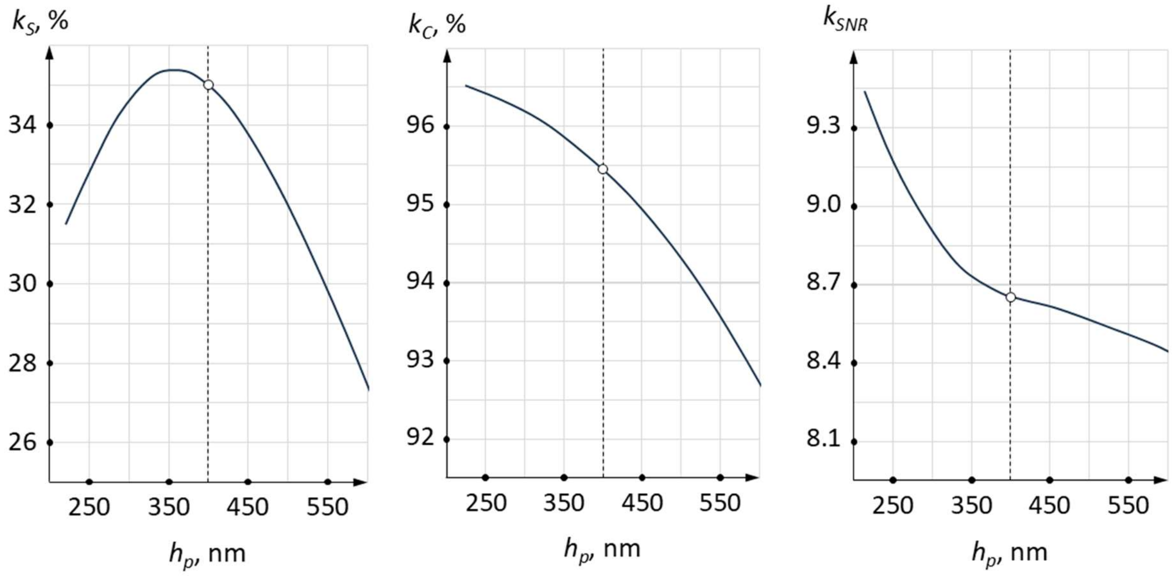
- k_S — coefficient of useful signal, expressed as the ratio between the effective photoluminescent component and the maximum signal attainable when the beam is focused on a pit of the first information layer;
- k_C — contrast coefficient, determined as the ratio of the effective (useful) photoluminescent signal to the mean signal level registered by the detection system;
- k_{SNR} — SNR parameter, calculated as the ratio between the effective signal and the magnitude of stochastic noise that remains indistinguishable in the detection process.

These indicators serve as essential metrics for evaluating the efficiency, stability, and fidelity of data retrieval in multilayer PMD-based optical storage systems:

$$\left[\begin{array}{l} k_S = (I_{SN} - I_N)/I_S^+ \\ k_S = (I_{SN} - I_N)/I_{SN} \;, \\ \Delta k_S = I_{SN}/\Delta I_{SN}^+ \end{array}\right. \tag{3}$$

where I_N is useful component signal amplitude, I_N is parasitic component of signal amplitude, I_{SN} is signal amplitude which includes both the useful and parasitic components, ΔI_S^+ is maximum deviation in the signal amplitude when the probing beam is focused on a pit, ΔI_{SN}^+ is maximum deviation in the signal amplitude when the probing beam is focused on a land.

The initial stage of the study involved determining the optimal pit depth. According to preliminary estimates, the optimal value was expected to be approximately $h_p \cong 600$ nm. However, results of computer modeling indicated that at this depth, the absorption of each information layer



(a) (b) (c)

Figure 2: Dependences of the useful signal (a), contrast (b) and SNR (c) indicators on pit depth

increased significantly. Therefore, for volumetric data storage media, a pit depth of approximately $h_p \cong 350$ nm was found to be more appropriate. Considering that the spatial resolution of the developed computational model is 100 nm, the value $h_p \cong 400$ nm was selected for further simulations (Figure 2). This value was subsequently used in calculations for PMD media employing pyrazoline-based recording materials. It should be noted that while variations in pit depth had a relatively minor impact on contrast and SNR indicators, as illustrated in Figures 2, the value $h_p \cong 400$ nm also proved to be more suitable in this case.

The next stage involved determining the minimum land length of the information layer in the PMD. It is evident that, in order to maximize the surface storage density of the information layer, it is desirable to minimize this parameter. However, a decrease in land length inevitably increases the absorption within the information layer, which leads to a substantial reduction in the level of the useful signal.

On the other hand, increasing the land length beyond a certain point introduces challenges for the tracking system during the readout. This trade-off complicates the optimization of the target function, as it becomes difficult to account for both the signal degradation and tracking reliability in a single maximization criterion (Figure 3). Therefore, for the purpose of subsequent calculations, the initial minimum land length was retained at approximately $l_p \cong 350$ nm.

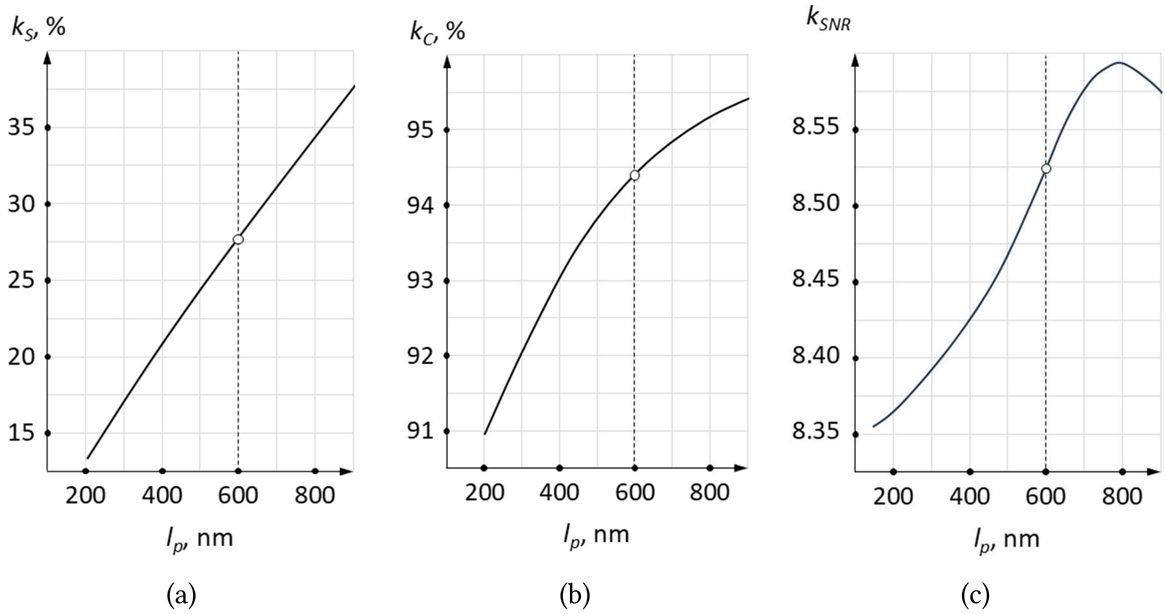
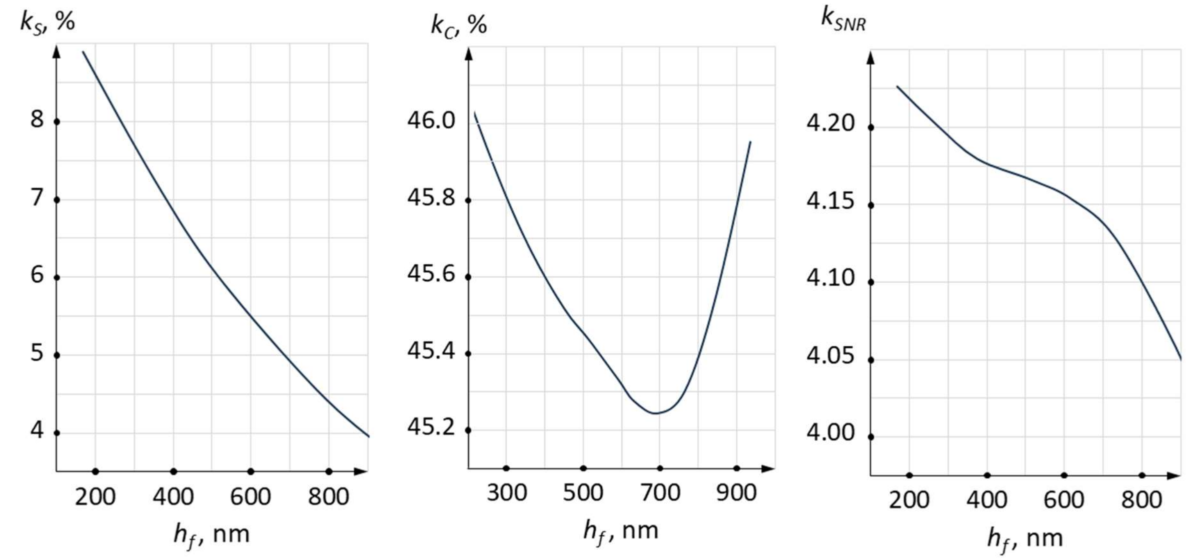


Figure 3: Dependences of the useful signal (a), contrast (b) and SNR (c) indicators on land size

During the course of the study, a novel approach was proposed that combines the principles of both multilayer and multilevel optical data recording. The multilevel recording technique is based on encoding multiple bits of information within a single physical pit on the optical medium. In this context, the number of recording levels n (with $n = 8$ selected for the purposes of this model) results in an n-fold increase in both the surface data density and the potential data readout speed. However, the improvement is accompanied by a corresponding decrease in the amplitude of the useful signal, which increases its vulnerability to noise and consequently lowers the signal-to-noise ratio during the readout stage. Within the proposed system, two distinct implementations of multilevel encoding were considered, depending on the type of PMD. In PMD-ROM (Read-Only Memory), data are encoded by varying the depth of the surface relief pits, with each depth corresponding to a particular information level. In PMD-R (Recordable), multilevel recording is achieved by modulating the degree of photobleaching in the recording material, allowing multiple distinguishable optical states within a single recorded area. Despite the physical differences in encoding mechanisms, the simulation results obtained within the constructed theoretical model showed only minor variation in the performance of these two formats, particularly in terms of signal integrity and readout quality (Figure 4). This suggests that both approaches are viable for practical implementation in high-capacity optical data storage systems. Computer simulations revealed that although the minimum amplitude of the useful signal decreased due to the implementation of multilevel encoding, the noise level also decreased proportionally. As a result, the contrast ratio and SNR did not decline by a factor of eight as might be expected given the eight-level encoding but were instead reduced only by approximately half.



(a) (b) (c)

Figure 4: Dependences of the useful signal (a), contrast (b), and SNR (c) on the focusing depth of the probing beam in a multilayer structure with 8-level pits.

This finding indicates the potential viability and efficiency of combining multilayer and multilevel optical recording techniques within a unified storage system. Moreover, it should be stressed that employing multilevel encoding within a single information layer substantially increases its storage density, thereby decreasing the number of layers needed to reach a specified total capacity. This, in turn, leads to a substantial improvement in the overall reliability and mechanical stability of the optical disc, as fewer layers mean reduced complexity in alignment, fabrication, and error propagation across layers.

The results of this study indicate that the combination of multilayer and multilevel optical recording offers a promising direction for increasing data density in next-generation optical storage systems. However, as the number of layers increases, the probability of structural inaccuracies in the information layer rises proportionally, potentially degrading signal quality and system reliability. In this context, the use of direct laser writing (DLW) emerges as a highly promising solution [5]. A technology for direct laser writing of code sequences on modulation disks has been developed and experimentally validated, demonstrating superior precision and reliability in forming structural elements of the optical medium. Compared to traditional contact lithography, DLW offers significant advantages, particularly in the formation of submicron-sized features, due to its high spatial resolution and flexibility in parameter adjustment. These properties make DLW especially well-suited for multilayer optical structures, where the need for accurate alignment and reproducibility increases with the number of layers.

Conclusions

1. Long-term data storage requirements. Effective large-scale archiving demands technologies that combine cost-efficiency, scalability, and robust protection against information loss.

2. Limitations of traditional methods. Conventional near-field optical recording techniques, while capable of enhancing density, are constrained by high implementation costs and system complexity.
3. Current research directions. Modern efforts emphasize multilevel encoding, multilayer recording architectures, and the application of nanostructured photoluminescent compounds.
4. Material development. A new class of pyrazoline-based substances was synthesized, exhibiting high optical stability, adjustable luminescent characteristics, and strong light absorption.
5. Matrix integration and treatment. Embedding the compounds into a zeolite framework followed by laser processing further enhanced their functional performance.
6. Structural optimization. Adjustments to the information layer (particularly pit depth and land length) were found to directly affect both achievable recording density and the reliability of readout.
7. Modeling insights. Simulation results highlighted the importance of balancing signal amplitude and tracking stability between layers.
8. System-level improvements. Combining multilevel encoding with the use of diverse luminescent materials across layers increased overall storage capacity and precision of data retrieval.

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Declaration on Generative AI

The authors have not employed any Generative AI tools.

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