



Section 5. Technical sciences in general

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INTERLEAVED RECORDING OF FORMATTING MARKS IN THREE-DIMENSIONAL OPTICAL INFORMATION CARRIERS: REDUCING FORMATTING TIME FOR MULTILAYER STORAGE MEDIA

*Alexey Viktorovich Morozov*¹

¹ Research and Educational Center for Photonics and Optical IT, School of Physics and Engineering, ITMO University, Saint Petersburg, Russian Federation

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Abstract

Formatting time scales with the number of independently addressed layers in a volumetric optical carrier, a relationship that recent gains in per-layer data density have made increasingly costly. This paper examines the interleaved formatting method disclosed by Polshchikov I., in which servo marks are recorded along radial and axial paths matched to a three-dimensional lattice, replacing the spiral track later used for reading. For a representative carrier with 37,000 spiral tracks, the disclosed method reduces recording-head travel distance from approximately 9415 m to approximately 22 m per formatted layer and reduces the required number of head rotations by a factor of roughly 66. Combined radial-axial interleaving raises recording rate by at least a factor of twelve over spiral-following formatting. The analysis identifies group-to-group transition distance, specified in the disclosure at 30 to 70 microns, as the parameter most likely to constrain further throughput gains, and proposes testing whether synchronous-movement recording strategies documented in holographic storage transfer to axial refocusing in discrete-layer carriers.

Keywords: *Three-dimensional optical storage, formatting time, multilayer recording, interleaved recording*

1. Introduction

The storage capacity in a volumetric optical carrier increases with the number of independently addressed layers. The servo infrastructure required to make each layer readable does not become cheaper to pro-

duce as the number grows. A carrier built to hold 20 formatted layers requires roughly 20 times the positional reference recording effort of a single-layer disc because conventional formatting scans a recording head along the full spiral track separately for

every layer (Polshchikov I., 2025). Materials research has pushed layer counts and per-site information density upward, making the relationship more consequential. Wang *et al.* (Wang H., Lei Y., Wang L., Sakakura M., Yu Y., Shayeganrad G., *et al.*, 2022) reported error-free five-dimensional recording across 100 layers in silica glass using anisotropic nanopore modification that preserves greater than 99 percent visible-range transmission through each preceding layer; this transmission figure makes deep multilayer stacks optically viable. Park *et al.* (Park C. H., Petit Y., Canioni L., Park S. H., 2020) demonstrated a distinct route to the same goal, encoding two independent 4-bit bitmap images within a single glass volume by multiplexing the ellipse orientation and fluorescence intensity against a 16-by-16 calibration matrix, so that each recorded site carries more information without requiring additional physical layers. Neither study reported the time required to produce the positional reference structure a playback system would need to locate and read these sites. Both treat data-layer capacity as the variable of interest and leave the layer-addressing cost unexamined.

This gap recurs across several studies in the same subfield. Gu *et al.* (Gu M., Zhang Q., Lamon S., 2016) surveyed metallic nanoparticles, graphene and graphene oxide, semiconductor quantum dots, and rare-earth-doped nanocrystals as optical storage media, organizing the field around capacity, lifetime, and energy consumption; formatting or servo-layer production does not appear as a design parameter anywhere in that framework. Yu *et al.* (Yu J., Luo M., Lv Z., Huang S., Hsu H. H., Kuo C. C., *et al.*, 2020) extended the same materials-first framing to luminescent nanomaterials, distinguishing upconversion, long-persistence, and downconversion mechanisms by their optical readout properties; the cost of writing the coordinate structure on which these mechanisms depend plays no part in that classification. Dai *et al.* (Dai D., Zhang Y., Yang S., Kong W., Yang J., Zhang J., 2024) reviewed rare-earth nanoparticles, graphene, and diarylethene compounds under the same organizing principle. Collectively, these three reviews show a developed vocabulary for comparing storage density and lifetime across chemically

unrelated media. No equivalent vocabulary exists for comparing the production cost of the addressing structures that media require once assembled into multilayer carriers. Yan *et al.* (Yan Z., Hu J., Xiao Z., Xie D., Cao Q., Gan Z., *et al.*, 2023) directly named this omission: their review noted that Blu-ray-derived multilayer storage remains capacity-limited by a fixed, predefined layer count precisely because each additional layer carries a fixed addressing cost. The review distinguishes multidimensional encoding, which packs more bits into each diffraction-limited voxel, from super-resolution encoding, which creates diffraction-unlimited voxels through controlled photoexcitation and photoinhibition. Both strategies increase the density per layer; neither changes the cost of addressing a layer once it exists.

The second branch of the field bypasses the discrete layers entirely. Chen *et al.* (Chen R., Wang J., Wu H., Song M., Yang Y., Lin D., *et al.*, 2026) recorded data holographically by jointly encoding the amplitude, phase, and polarization within a single data page, using a convolutional neural network to decode the three properties from intensity measurements alone. Information is distributed volumetrically through interference, with no fixed set of physical depths assigned; therefore, no layer count exists for a formatting pass to scale against in the sense that constrains the media reported in (Wang H., Lei Y., Wang L., Sakakura M., Yu Y., Shayeganrad G., *et al.*, 2022; Park C. H., Petit Y., Canioni L., Park S. H., 2020). Liu *et al.* (Liu H., Zheng S., Chen X., Lin Z., Lin Y., Wang J., *et al.*, 2026) reported a holographic recording technique that increases the writing speed by synchronizing the movement of the recording medium with that of a spherical reference wave, a strategy that reduces the dead time between recording events without changing their number. Chen *et al.* (Chen X., Liu H., Zheng S., Wang J., Chen R., Ke S., *et al.*, 2026) achieved capacity gains through hybrid angle-polarization multiplexing within the same holographic framework, again without introducing additional physical layers. Wu *et al.* (Wu J., Peng L., Wu H., Xiong R., Huang J., Wu E., *et al.*, 2026) worked at the material level within this branch, addressing photopolymer

stability and repeatability constraints in PQ/PMMA media. The stability and repeatability constraints they address indicate that holographic storage carries a throughput bottleneck of its own, located in material degradation and reference beam alignment, separate from layer-by-layer addressing cost.

Anderson *et al.* (Anderson P., Aranas E., Assaf Y., Behrendt R., Black R., Caballero M., *et al.*, 2023; Anderson P., Aranas E., Assaf Y., Behrendt R., Black R., Caballero M., *et al.*, 2025) described a third variant of this trade-off at the system scale. Project Silica writes data into quartz glass platters designed to remain untouched for their entire service life, eliminating the periodic media refresh that magnetic storage requires roughly every five years for hard disk drives (HDDs). The system's central design goal is that formatted media never need to be revisited once they are written. This goal is compatible with either branch of the materials literature. It changes the economic weight of formatting time: a system built around write-once, permanently archived carriers amortizes any fixed per-carrier formatting cost across the entire archival lifetime of the carrier. Therefore, a reduction in formatting time compounds differently at the data-center scale than for a single disc produced for consumer use.

Kazansky *et al.* (Kazansky P.G., Lei Y., Wang L., Yu Y., Wang H., Sarao B., 2020) and Zhou *et al.* (Zhou J.W., Su J., Guan J., Yang Y., Ji W., Wang M., *et al.*, 2024) represent a fourth line of development, pursuing storage lifetime and density through material choice: quartz glass in the former case and diamond fluorescent vacancy centers in the latter, with Zhou *et al.* reporting a storage density of 14.8 terabits per cubic centimeter and a per-site write time of 200 femtoseconds. Neither paper addresses how positional reference information is produced across a growing number of storage centers within a fixed volume, the same omission identified above in the nanomaterials reviews, applied here to a defect-center medium.

Polshchikov (Polshchikov I., 2025) directly addressed this omission by treating the sequence in which formatting marks are recorded as a variable independent of the geometry of the servo pattern itself. Their disclosure identifies the transit time between locations

where consecutive marks are recorded as the rate-determining factor in conventional formatting, and the duration of an individual recording pulse contributes far less to the total formatting time. The disclosure proposes reordering the transit path to follow the coordinate axes of the underlying three-dimensional lattice, replacing the spiral track that would otherwise guide playback.

2. Materials and Methods

Polshchikov (Polshchikov I., 2025) described a carrier whose body could be monolithic or assembled from multiple plates bonded with an optically active adhesive. The active moiety responds to laser irradiation through two-photon absorption, allowing marks to be recorded at controlled depths without disturbing adjacent layers. Data occupy a series of virtual layers separated by roughly 10 to 15 microns; formatting marks occupy a sparser, separate set of layers interspersed among them. This physical separation between data layers and formatting layers makes the recording sequence for the latter an independent design variable, because a formatting layer need not be produced in the same pass or by the same path as the data it will later help address.

The spatial arrangement of the formatting marks follows a three-dimensional lattice defined by the intersection of three surface families: equidistantly spaced cylindrical spiral tracks, equiangular spaced radial planes, and recording planes substantially orthogonal to the radial planes. Each intersection point constitutes the lattice node. A mark is recorded within a tolerance zone around that node, which is sized to a fraction of the interlayer spacing, sufficient for servo positioning. This tolerance permits reordering: the addressable unit is a node, and any traversal that visits every node satisfies the formatting requirements.

Radial formatting exploits this freedom by exchanging the roles of the conventional formatting assigned to the head and carrier. The head executes a fast reciprocating motion along a radius, while the carrier advances in discrete angular steps, remaining static during each recording event (Polshchikov I., 2025). In contrast, conventional formatting holds the carrier's angular position fixed while

scanning the head along a spiral. The angular spacing between successive radii was set to intersect every mark on the outermost track at a fixed interval, producing a constant angular velocity servo pattern: linear mark spacing decreased toward the center, while the angular spacing remained uniform. The scheme can also be executed by the continuous rotation of both the head assembly and carrier. The head then traces radial arcs whose curvature a matched carrier rotation compensates, so recorded marks fall along true radii and not along the arcs that the head itself traces.

Axial formatting addresses the layer dimension by refocusing the recording beam along its optical axis while the carrier rotates continuously; thus, marks intended for different depths are recorded during a single pass along a track, replacing separate passes for each layer. Refocusing occurs through a differential-thread lens actuator, which shifts a movable lens by a fraction of a millimeter per rotation, or through an electro-optical refractive-index modulator that changes the beam divergence and, therefore, the focal depth within nanoseconds. Interleaving marks across several layers during one scan requires refocusing faster than any mechanical actuator can move, and this speed requirement makes the electro-optical route necessary: a modulator that changes divergence within the recording beam path avoids the inertial delay that a lens actuator would otherwise impose between successive layers. The carrier continues to rotate during refocusing; thus, marks recorded at successive depths are displaced angularly relative to each other, producing a lattice tilted with respect to the beam's optical axis. The disclosure specifies that after one complete carrier rotation, any nodes left unaddressed by this tilted pattern are filled in, restoring the intended grid without requiring the recording sequence to directly correct for the tilt.

The apparatus supporting concurrent multi-carrier formatting mounts a plurality of spindles, each carrying one carrier and rotating about its own axis, on a stage that is centered on a common central axis. A separate platform above it carries a corresponding array of recording units that rotate about the same axis. The platform and spindle rotation are synchronized so that the optical

axis of each recording unit traces radial arcs on the carrier beneath it, following the relationship $\alpha = 360^\circ k/M$, where α is the angle each spindle rotates during one platform revolution, k is the number of radial planes intersecting the layer being recorded, and M is the number of recording units in operation. This relationship allows the formatting throughput to scale with the number of recording units deployed, independent of any single unit's recording speed, because each additional unit constitutes an independent channel operating on its own carrier or depth range. A small compensating rotation, on the order of fractions of a micron in linear displacement, corrects for the continuously changing radius of the spiral tracks as marks are recorded on successive tracks, preventing the accumulation of radial drift across a full platform rotation (Polshchikov I., 2025).

3. Results

For a carrier with an average track diameter of 81 mm, bounded by a maximum recordable diameter of 118 mm and a minimum of 44 mm, and a track pitch of approximately 800 nm, the active recording area supports approximately 37,000 spiral tracks (Polshchikov I., 2025). Conventional spiral-following formatting requires the head to travel the full cumulative length of these tracks (approximately 9415 m) for each formatted layer. At a rotation speed of 100 Hz, the maximum sustainable centrifugal and vibrational constraints on the carrier correspond to a travel distance of approximately six minutes per layer.

Radial formatting replaces spiral traversal with radial traversal across an active area width of approximately 37 mm, using approximately 600 radii to match the mark count on the outermost track (Polshchikov I., 2025). The total head travel per formatted layer fell to approximately 22 m, a reduction by a factor of approximately 430 relative to spiral-following formatting. The number of head rotations required decreased from approximately 37,000 to 600, a reduction by a factor of approximately 66. Individual marks are recorded with pulses shorter than one microsecond, typically around 100 ns. The disclosure attributes the bulk of the time savings to reduced travel distance, and the

pulse duration remains the same between the two schemes.

The mark spacing changes accordingly. Conventional formatting records marks at spacings matched to data readout requirements, typically hundreds of microns along the track, with the carrier rotation speed limiting the recording rate to hundreds of kilohertz. Under radial formatting, consecutive marks along the radius correspond to adjacent spiral tracks. Therefore, intermark spacing falls to approximately one micron, permitting a higher recording rate without any increase in the pulse generation speed. When axial and radial interleaving are combined, for example, recording marks at three spiral radii and four depths within one coordinated scan, the disclosure reports a resulting recording rate at least 12 times higher than that achieved by spiral-following formatting, despite marks still being recorded in sequence (Polshchikov I., 2025).

This twelvefold figure is not directly comparable to the write-speed figures reported elsewhere in the optical storage literature because the two sets of numbers describe different processes. Wang *et al.* (Wang H., Lei Y., Wang L., Sakakura M., Yu Y., Shayeganrad G., *et al.*, 2022) reported a data-layer writing speed of 8 kilobytes per second for their 100-layer birefringent glass medium; this figure describes the user-data throughput after formatting is complete. It says nothing about the rate at which the formatting layers are produced. Zhou *et al.* (Zhou J. W., Su J., Guan J., Yang Y., Ji W., Wang M., *et al.*, 2024) reported a 200-femtosecond write time per fluorescent vacancy center in diamond, describing the duration of a single data-bearing event. This figure likewise says nothing about the aggregate time needed to populate a positional reference grid across an entire carrier. Polshchikov's (Polshchikov I., 2025) twelvefold figure describes formatting throughput specifically, the rate at which the coordinate structure a subsequent data-recording pass depends on, is produced. This is the quantity missing from each capacity-focused paper discussed in the Introduction.

The depth range achievable within a single lens configuration constrains the number of layers that can be grouped together before the focal point must be repositioned by other

means (Polshchikov I., 2025). For two-photon absorption media recorded at a numerical aperture of 0.65, the interlayer distance between adjacent data-bearing layers falls between 4 and 10 microns. A single lens can focus without spherical aberration correction across approximately 100 μm of depth, supporting groups of approximately 20 layers recorded with a simplified single-lens optical system. The groups were separated from each other by 30 to 70 microns. This distance reflects the accuracy achievable when transitioning the focal point between groups, which is distinct from the interlayer spacing within one group. The group-to-group transition distance, which is an order of magnitude larger than the interlayer spacing, is identified in the Discussion as the most likely constraint on further throughput improvement.

Quality control following optical formatting verifies six parameters (Polshchikov I., 2025): axial distance between formatted layers, parallelism of the layers to each other and to the disc surface, accumulated axial position deviation error across the layer stack, distance between formatting marks within each layer and any differences in that distance between layers, distance between the first surface and the first recorded layer, and the distance between the last surface and the last recorded layer. These parameters target the principal failure mode of the interleaved method. A newly formatted layer group is referenced to a previously recorded layer, not to the original embossed reference; thus, positional errors can accumulate across successive groups. The disclosure specifies that after a bounded number of layers are formatted relative to one reference, the procedure resets, and a new group is formatted relative to a more recently verified reference. This reset limits the extent to which the accumulated error can propagate before correction.

4. Discussion

The travel distance reduction reported by Polshchikov (Polshchikov I., 2025) arises from reordering the path followed by the recording head. The mark density and mark shape remain unchanged, which is what makes the method complementary to the capacity-increasing strategies surveyed in the Introduction. A carrier formatted with 100 birefringent

layers using the approach reported by Wang *et al.* (Wang H., Lei Y., Wang L., Sakakura M., Yu Y., Shayeganrad G., *et al.*, 2022) still requires the same lattice of positional reference points, whether the lattice is produced by spiral-following or interleaved traversal. The interleaved method only changes the production cost of a servo structure whose geometry and function remain the same. The unchanged servo geometry is the reason why the twelve-fold formatting-rate figure and the 100-layer density figure reported in (Wang H., Lei Y., Wang L., Sakakura M., Yu Y., Shayeganrad G., *et al.*, 2022) describe complementary quantities. The omission identified in the Introduction, that materials-focused papers do not report formatting costs, reflects separate development and reporting traditions between two lines of work that fit together without conflict.

The group-to-group transition distance of 30 to 70 microns constrains this fit more than the within-group interlayer spacing. This distance is set by the accuracy of the transition of the focal point between lens configurations, not by the optical properties of the recording medium; therefore, it applies independently of which capacity-increasing material occupies each group, whether nanograting-based glass (Wang H., Lei Y., Wang L., Sakakura M., Yu Y., Shayeganrad G., *et al.*, 2022), ellipse-orientation-encoded glass (Park C. H., Petit Y., Canioni L., Park S. H., 2020), or a defect-center medium such as diamond (Zhou J. W., Su J., Guan J., Yang Y., Ji W., Wang M., *et al.*, 2024). Reducing this transition distance would extend the number of layers a single group can cover before a reset to a new reference layer becomes necessary, and this extension would reduce the frequency of positional-error accumulation in the six quality control parameters exist to catch. The disclosure does not report whether the transition distance can shrink below its current range without degrading the axial position accuracy, which is the same accuracy that the quality control parameters verify (Polshchikov I., 2025). Whether further formatting-time gains beyond the twelvefold figure are achievable within the described apparatus or require a different refocusing mechanism remains open.

Liu *et al.*'s (Liu H., Zheng S., Chen X., Lin Z., Lin Y., Wang J., *et al.*, 2026) synchronous

movement recording technique for holographic storage offers one candidate mechanism worth testing against this constraint. Their method increases the write speed by coordinating the motion of the recording medium with that of a spherical reference wave, reducing the dead time between recording events in a volumetric medium with no discrete layers for transition. Polshchikov's (Polshchikov I., 2025) apparatus already coordinates the spindle rotation, platform rotation, and beam refocusing toward the same end within a discrete-layer architecture. Whether the synchronization principle reported in (Liu H., Zheng S., Chen X., Lin Z., Lin Y., Wang J., *et al.*, 2026), applied to axial refocusing, would reduce the group-to-group transition delay is a question that the current disclosure does not address, since the two methods were developed for architecturally distinct storage modalities and have not been tested against each other.

The design goal of Project Silica, which is to eliminate media refresh (Anderson P., Aranas E., Assaf Y., Behrendt R., Black R., Caballero M., *et al.*, 2023; Anderson P., Aranas E., Assaf Y., Behrendt R., Black R., Caballero M., *et al.*, 2025), reframes the importance of formatting-time reduction at the production scale. A storage system built around carriers that remain untouched for their entire archival life amortizes the fixed cost of producing each carrier's formatting layer across its entire life, not across a single read-write cycle. A reduction in per-carrier formatting time from minutes to seconds, therefore, compounds across the total number of carriers a data-center-scale archival deployment would require, not merely across the time to produce one disc. This connection concerns where formatting time savings accrue economically. This does not imply that silica glass platters use the interleaved formatting method described here; the disclosure examined in this paper concerns discrete spiral-track carriers, and nothing in the reports in (Anderson P., Aranas E., Assaf Y., Behrendt R., Black R., Caballero M., *et al.*, 2023; Anderson P., Aranas E., Assaf Y., Behrendt R., Black R., Caballero M., *et al.*, 2025), indicates that Project Silica's addressing scheme follows the same lattice structure.

One limitation constrains how far the reported figures can be generalized. A 430-fold

and 66-fold reduction in the travel distance and rotation count, respectively, was computed for a single carrier geometry with an 81-mm average track diameter and 800-nanometer track pitch (Polshchikov I., 2025). (The disclosure does not report how these ratios change for carriers with substantially different track pitches or diameters, and both vary considerably across the nanograting, fluorescence, and defect-center media surveyed above. The ratio between the spiral length and radial-formatting travel distance depends on the track pitch through the number of tracks per radius. A carrier formatted at a finer pitch to support the 100-layer density reported in (Wang H., Lei Y., Wang L., Sakakura M., Yu Y., Shayeganrad G., *et al.*, 2022) would require proportionally more radii per group, and this would reduce the travel-distance advantage that interleaved formatting provides relative to the example reported here.

5. Conclusions

Reordering the path along which formatting marks are recorded reduces the formatting time for three-dimensional optical carriers by more than two orders of magnitude in head travel distance and by a factor of approximately 66 in the required rotation count for the carrier geometry reported by Polshchikov (Polshchikov I., 2025). The mark geometry, mark spacing, and servo pattern of the encoded marks remain unchanged throughout this reduction. The gain addresses the cost of capacity-focused literature on multilayer and multidimensional optical storage, which has consistently been left unreported. Nanograting-based glass (Wang H., Lei Y., Wang L., Sakakura M., Yu Y., Shayeganrad G., *et al.*, 2022), fluorescence-encoded glass (Park C. H., Petit Y., Canioni L., Park S. H., 2020), luminescent nanomaterials (Gu M., Zhang Q., Lam-on S., 2016; Yu J., Luo M., Lv Z., Huang S., Hsu H. H., Kuo C. C., *et al.*, 2020; Dai D., Zhang Y., Yang S., Kong W., Yang J., Zhang J., 2024), and defect-center media (Zhou J. W., Su J., Guan J., Yang Y., Ji W., Wang M., *et al.*, 2024) each increase the number of layers or the per-voxel information density that a production process must eventually address;

none of these papers report the cost of addressing the production.

The 30-to-70-micron group-to-group transition distance identified in this analysis as the binding constraint on further gains sets the practical ceiling on how many layers a single formatting pass can cover before a reset to a new reference layer becomes necessary. Reducing this distance would directly extend the ceiling. Whether the synchronization principles reported for coordinated medium-and-reference-wave motion in holographic recording (Liu H., Zheng S., Chen X., Lin Z., Lin Y., Wang J., *et al.*, 2026) transfer to axial refocusing in a discrete-layer architecture remains untested; the two methods were developed for different storage modalities and have not been evaluated against each other. Testing this transfer would require measuring axial refocusing accuracy against reference-layer tracking error across transition distances narrower than the range specified in (Polshchikov I., 2025), and applying the same six-parameter quality control protocol defined there to each tested distance.

The second open question concerns the generalization across carrier geometries. The 430-fold and 66-fold reductions reported here apply to one-track pitch and one carrier diameter. Materials capable of supporting denser layer counts, such as the 100-layer birefringent glass reported in (Wang H., Lei Y., Wang L., Sakakura M., Yu Y., Shayeganrad G., *et al.*, 2022), typically require a finer track pitch, which increases the number of radii required per formatting group and narrows the travel distance advantage provided by interleaved formatting. Establishing how far this advantage narrows as the track pitch decreases would require formatting trials across the pitch range that the capacity-focused literature has already established as viable for high-density media, rather than a single representative case.

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© Morozov A. V.

Contact: ao.05@mail.ru