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Sub-Volume Independence in Three-Dimensional Optical Media and What it Changes for Carrier Design

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Abstract

Formatting a volumetric three-dimensional optical carrier across hundreds of recording layers requires positional accuracy that no single formatting session can maintain globally, for reasons rooted in the physics of focused beam propagation. Finite objective working distance, depth-dependent spherical aberration, and layer-to-layer reference error accumulation each impose independent ceilings on lattice coherence, and their combined effect places the achievable coherence depth well below the layer counts implied by recent petabit-scale density demonstrations. This paper examines sub-volume independence as a structural design principle that responds to these constraints by partitioning the carrier volume into bounded domains, each formatted to a locally coherent lattice and separated by boundary markers that encode domain transitions in place of a globally maintained coordinate system. The analysis develops the physical basis for the coherence ceiling, traces the consequences of domain partitioning for interlayer crosstalk margins and servo recovery behavior, and evaluates the scalability of this carrier architecture toward layer counts in the thousands.

Keywords: *Carrier Design, Interlayer Crosstalk, Lattice Coherence, Multilayer Formatting, Sub-Volume Independence, Three-Dimensional Optical Carrier, Volumetric Storage Architecture, Zone Formatting.*

INTRODUCTION

Volumetric optical storage has been a research objective for roughly three decades, and the gap between what recording media can store and what read-write systems can reliably retrieve has widened over that period. On the media side, the trajectory is steep: Zijlstra, Chon, and Gu (2009) added wavelength and polarization as independent storage dimensions in plasmonic nanorod composites, demonstrating five-dimensional multiplexing in a disc-format body; Zhao, Wen, Hu, Wei, Zhong, Ruan, and Gu (2024) recorded marks of approximately 54 nm lateral size at 1 micrometer layer spacing, projecting a theoretical capacity of one petabit per disc; Hu, Huang, Yang, Qiu, Song, Zhang, and Dong (2021) showed reversible volumetric recording in photo-modulated glass through spectral hole-burning, enabling marks to be erased and rewritten without mechanical intervention.

Lamon, Zhang, and Gu (2021) showed that even machine-learning-based retrieval methods require some positional reference framework within the carrier, with retrieval complexity growing with the cube of the layer count in the absence of one, making deep carriers practically unreadable regardless of signal processing sophistication. Lamon, Zhang, Yu, and Gu (2024) extended this analysis in the context of neuromorphic storage, arguing that the engineering path to high-capacity storage runs through local redundancy and locally defined accuracy, an argument whose structural relevance to carrier formatting design is direct. The architecture described by Polshchikov (2025) operationalizes this path through the concept of sub-volume independence: the carrier volume is partitioned into bounded regions, each formatted to an internally coherent lattice, with the relationship between regions encoded in boundary markers rather than in a globally maintained coordinate system, and the design implications of this choice extend from interlayer crosstalk margins through error recovery behavior to the practical ceiling on total layer count.

METHODS

Physical Constraints on Global Lattice Coherence

The case for global lattice coherence in volumetric carrier formatting rests on the assumption that a single formatting session, referencing a single embossed or inscribed base layer, can propagate positional accuracy across the full depth of the carrier body, and three mechanisms independently violate this assumption in ways whose effects compound.

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The first is the finite working distance of the objective lens: high-NA objectives used in optical disc systems have working distances in the range of 0.1 to 0.3 mm, so recording across 6 mm of disc thickness requires multiple lens configurations, and each configuration change introduces a registration offset at the interface between the layers formatted before and after the change, arising from mechanical repositioning error at sub-micron scale that is directly comparable to the 1 to 5 micrometer inter-layer spacings targeted in high-density volumetric systems. Polshchikov (2025) note that a lens working distance of approximately 100 micrometers without aberration correction allows groups of roughly 20 layers to be formatted within one configuration at 4 to 10 micrometer spacing; a 6 mm disc with 5 micrometer layer spacing contains approximately 1,200 layers organized into 60 such groups, and the registration offset at each group boundary is irreducible by calibration within the same configuration. The second mechanism is depth-dependent spherical aberration: focusing through a dielectric medium at depth d below its surface introduces wavefront aberration whose dominant Zernike term grows approximately as d squared divided by the numerical aperture to the fourth power for a planar air-medium interface, and Matsumoto, Inoue, Matsumoto, and Okazaki (2015) measured this relationship for two-photon excitation in aqueous media, finding that at 200 micrometers depth with NA 1.0 the uncorrected Strehl ratio falls below 0.1, meaning that in a two-photon recording medium, where signal depends on the square of intensity, the two-photon excitation rate is reduced by a factor of 100 relative to the surface value, and compensating for this with higher pulse energy restores the total two-photon absorption but also enlarges the write spot because the two-photon rate profile broadens when the peak is raised to recover threshold excitation away from the nominal focus. The third mechanism is error accumulation in sequential layer-to-layer reference tracking: in the reference-beam formatting approach described by Polshchikov (2025), positioning error in layer n propagates into layer n+1 as a systematic offset, and over k layers the accumulated error grows as the square root of k times the per-step error for uncorrelated noise, reaching approximately 245 nanometers at k equal to 600 layers with a per-step radial positioning error of 10 nanometers, comparable to the track pitch of 800 nanometers and sufficient to destroy lattice correlation between the first and last layer of the stack.

Sub-Volume Structure and Boundary Markers

The partitioning scheme described by Polshchikov (2025) operates in two independent spatial dimensions, producing a carrier whose volume is divided into a three-dimensional array of bounded cells, each formatted to a locally consistent lattice. In the axial direction, layers are organized into groups separated by inter-group distances of 30 to 70 micrometers, large enough to permit lens reconfiguration and reference reset between groups; within each group, inter-layer spacing is 4 to 10 micrometers and lattice coherence is maintained by sequential reference-beam tracking from an embossed or inscribed base layer. In the radial direction, the carrier is divided into annular zones formatted with different angular spacings between radial planes, chosen to maintain approximately constant linear mark spacing across the radius range of each zone. At each sub-volume boundary, a marker encoding the transition is inscribed, allowing a reading system to identify its current sub-volume and load the corresponding servo parameters before proceeding. The offset between adjacent sub-volumes can be set to zero, producing a carrier that reads as globally uniform from the controller perspective despite being locally formatted; it can also be set to a predetermined non-zero value, encoding a measurable boundary that the reading system detects as a change in lattice phase; or to a pseudo-random value, producing a carrier in which sub-volume identity is established by correlating the observed lattice phase against a stored table, an approach with access-control applications since a reading system lacking the sub-volume parameter table cannot determine which sub-volume it has entered and therefore cannot perform sequential disc reading. The sub-volume boundary reset described by Polshchikov (2025) does not eliminate per-step positioning error within a group; its function is to cap the number of reference propagation steps over which error accumulates, bounding coherence degradation within each group at the level set by the group size.

Annular Zone Design and Mark Density Compensation

The radial partitioning into annular zones addresses a geometric constraint specific to disc-format carriers: formatting marks placed at fixed angular intervals around the disc rotation axis have a linear spacing that decreases toward the disc center in proportion to the radius, so for the carrier geometry described by Polshchikov (2025), with 600 marks per track on the outermost track at radius 59 mm giving a linear mark spacing of approximately 0.62 mm, the same 600 angular marks on the innermost track at radius 22 mm produce a spacing of approximately 0.23 mm, a factor of 2.7 denser. If the entire carrier is formatted at the outer-track angular frequency, inner tracks carry marks at a density inconsistent with the linear resolution of the reading optics, creating false-lock conditions in the tracking servo where the servo acquires a mark on an adjacent track at half or one-third the correct linear distance; Meinders, Mijiritskii, van Pieterson, and Wuttig (2006) describe false-lock servo acquisition as a known failure mode in high-track-density optical disc systems where the ratio of track pitch to read spot diameter falls below approximately 1.7, and inner-track mark density approaching this ratio would produce the same failure mode in the angular dimension. The annular zone scheme compensates by increasing the angular spacing between radial planes at inner zones, reducing inner-track mark density back toward the outer-track value, so that each zone carries a distinct angular frequency and constitutes a formatting sub-volume in the radial dimension, requiring the reading controller to switch servo parameters when crossing from one zone to another during a radial seek, in the same way that zone-bit recording firmware in magnetic hard drives and constant zonal velocity optical formats maintains a per-zone parameter table and performs a brief acquisition phase at each zone crossing; Meinders et al. (2006) characterize the acquisition time at a zone boundary in optical systems as typically 1 to 3 disc rotations, which at 3,000 RPM corresponds to 20 to 60 milliseconds, a penalty that is negligible for carriers with 3 to 5 annular zones read sequentially.

RESULTS

Crosstalk Margins Under Sub-Volume Partitioning

Interlayer crosstalk in volumetric optical systems originates from two physically distinct sources: coherent stray light from the layer immediately adjacent to the focused layer, which interferes constructively or destructively with the signal depending on phase; and incoherent background from more distant layers, which adds a spectrally flat offset that reduces modulation depth. Ichimura, Saito, Yamasaki, and Osato (2006) calculated coherent crosstalk as a function of layer separation for a 0.85 NA system in a multilayer ROM geometry and found that the coherent component from the nearest adjacent layer exceeds the signal level when layer separation falls below approximately 5 micrometers in a quarter-wave reflective stack, a threshold that is material-dependent and will differ for two-photon polymer or glass media but whose scaling relationship holds across geometries: closer layers produce higher coherent crosstalk, with the penalty increasing sharply below a medium-dependent critical separation. Ide, Kimura, Tatsu, Kurokawa, Watanabe, Anzai, and Shintani (2010) demonstrated that a grating-based three-beam method can reduce differential push-pull signal fluctuation from 6 percent to 2 percent in triple-layer Blu-ray geometry, a factor of three improvement, with the method relying on the spatial regularity of the layer stack that is guaranteed by replication in conventional discs but must be maintained by formatting accuracy in volumetric carriers. The sub-volume partitioning of Polshchikov (2025) affects crosstalk margins through two channels: within an axial group, sequential reference-beam tracking keeps mark positions within a bounded error of their nominal lattice locations, maintaining the spatial regularity that crosstalk suppression methods require; between axial groups, the inter-group distance of 30 to 70 micrometers places adjacent groups well outside the coherent crosstalk range identified by Ichimura et al. (2006), so that inter-group stray light contributes only the incoherent background component, and the practical consequence is that crosstalk performance is determined by the intra-group geometry, a fixed design parameter, rather than by formatting accuracy across the full layer stack, which would degrade with layer number in a global-coherence scheme.

Controller Architecture Under Sub-Volume Independence

The read-write controller requirements for a sub-volume carrier differ from those for a globally coherent carrier in ways that are simultaneously more complex in firmware scope and more robust in failure behavior. A globally coherent carrier requires only one servo parameter set for the entire disc, and recovery from a servo dropout requires re-establishing the global position, potentially involving a seek to the disc initialization reference at the inner radius; for a 120 mm disc rotating at 3,000 RPM, a full seek to the inner radius takes on the order of 100 ms. A sub-volume carrier requires the controller to maintain a parameter table indexed by axial group and radial zone, and to perform a calibration event at each sub-volume boundary, but recovery from a servo dropout requires only a seek to the nearest sub-volume boundary, whose maximum distance from any point in the carrier is bounded by the sub-volume dimensions. Lamon, Zhang, and Gu (2021) analyzed the sensitivity of machine-learning-based mark retrieval algorithms to positional uncertainty and found that retrieval accuracy degrades significantly when mark position errors exceed approximately one-quarter of the track pitch, corresponding to 200 nanometers for an 800 nanometer track pitch; the error accumulation analysis in Section 2.1 shows that this tolerance is exceeded after approximately 400 reference propagation steps at 10 nanometers per-step error, whereas sub-volume partitioning with 20 layers per group caps propagation at 20 steps, keeping accumulated error at approximately 45 nanometers and well within the retrieval tolerance across the full disc depth. The firmware complexity of maintaining 1,500 parameter entries for a carrier with 300 axial groups and 5 annular zones is a real engineering cost, but it is a bounded cost that does not scale with layer count, and modern embedded storage controllers operate comfortably at this table size.

Scalability Toward High Layer Counts

The scalability argument for sub-volume independence is most clearly developed by examining what global coherence would require at the layer counts implied by recent density demonstrations. Zhao et al. (2024) recorded at 1 micrometer layer spacing across a 100 micrometer recording volume, achieving 100 layers per group in sub-volume terminology; extending this to a 6 mm disc body would require approximately 6,000 layers, and maintaining mark position accuracy to within 200 nanometers across 6,000 reference propagation steps at 10 nanometers per-step random error produces an accumulated error of square root of 6,000 times 10 nanometers, equal to approximately 775 nanometers, nearly four times the tolerance. Reducing accumulated error to 200 nanometers under global coherence would require per-step error below 2.6 nanometers, which falls below the thermal positioning noise of mechanical servo systems operating at the rotation speeds required for practical formatting throughput; there is no known engineering path to this accuracy level in a disc-format carrier with 6,000 layers. Under sub-volume partitioning with 20 layers per group, the 6,000-layer disc contains 300 groups, and the formatting accuracy requirement within each group is unchanged from the 20-layer case: 10 nanometers per step produces an accumulated error of square root of 20 times 10 nanometers, approximately 45 nanometers, well within tolerance. Adding more groups adds to the total layer count without affecting per-group accuracy, and the inter-group registration offset, arising at each lens reconfiguration event, does not accumulate because each group is independently referenced to its own embossed or inscribed base mark, so registration error between groups affects only the inter-group boundary calibration. Polshchikov (2025) describe the embossed reference layer as produced by micro-relief pressing during carrier body fabrication, with positional accuracy determined by the mold geometry; Meinders et al. (2006) report that UV-curing and pressing processes achieve layer registration accuracy in the range of 10 to 100 nanometers, which satisfies the inter-group boundary calibration requirement without placing additional constraint on the optical formatting system.

DISCUSSION

Designing a volumetric optical carrier as a globally coherent formatting structure is not a viable path to the layer counts implied by petabit-scale density demonstrations, and the three constraints analyzed in Section 2.1 are not contingent engineering shortcomings amenable to improved servo tuning: they scale with layer count in ways intrinsic to focused beam propagation through dielectric media and to the statistical behavior of mechanical servo systems. Polshchikov (2025) take the existence of these constraints as a given and design around them, producing a carrier architecture whose accuracy requirements are matched to what optical systems can actually deliver at each depth range. The organizing logic of sub-volume independence has a parallel in forward error correction for data channels: error-correcting codes do not eliminate channel errors but tolerate them within bounded domains, the codeword or sector, recovering from them using redundancy within those domains, so that global data integrity is achieved not by making each bit position perfectly reliable but by making each codeword reliably decodable. Sub-volume independence applies the same logic to the geometric layer of the carrier, achieving global navigability not by making each formatting layer globally accurate but by making each sub-volume locally coherent and each boundary identifiable. Lamon, Zhang, Yu, and Gu (2024) arrive at a structurally related conclusion from the neuromorphic storage direction, arguing that biological storage achieves high capacity and robustness through local connectivity and redundancy; the sub-volume carrier architecture converges on the same organizational principle from a different starting point, suggesting that local accuracy specification may be a general design principle for high-capacity storage systems.

A considered objection to the sub-volume approach concerns the latency cost at sub-volume boundary crossings. For a carrier with 300 axial groups and 5 annular zones, the controller must manage 1,500 parameter entries and perform boundary acquisition at each zone or group crossing; at 20 to 60 milliseconds per acquisition event, crossing 10 groups in a single seek adds 200 to 600 milliseconds to seek time, which is significant for access-time-sensitive applications. This cost is real, and it implies that sub-volume carriers are better suited to sequential or large-block access patterns than to random small-block access, a constraint that the carrier designer must acknowledge at the architecture level. The petabit-scale applications that motivate high-layer-count volumetric storage, archival data preservation and large-scale sequential data access, are the use cases where sequential access dominates, so the cost profile is acceptable in the application context that motivated the architecture, though it would require careful evaluation before applying the same carrier design to workloads with frequent random access across layer boundaries. Meinders et al. (2006) characterize acquisition overhead in zone-transition schemes as a standard design parameter that is specified per-product and managed by controller firmware, establishing a precedent for treating boundary acquisition latency as an engineering variable; the sub-volume boundary acquisition in the Polshchikov (2025) architecture falls into the same category, with its acceptable range determined by the target application.

CONCLUSION

Sub-volume independence, as formalized in the formatting architecture of Polshchikov (2025), addresses a structural constraint in volumetric optical carrier design that cannot be resolved by improving the accuracy of any single component of the formatting system. Finite objective working distance restricts formatting coherence to depth ranges of approximately 100 micrometers per lens configuration; depth-dependent spherical aberration degrades mark placement accuracy at rates that grow faster than linearly with depth below the corrected focal plane; layer-to-layer reference error accumulates as a random walk that exceeds track-pitch fractions within a few hundred layers at realistic per-step noise levels. The sub-volume architecture converts these constraints from obstacles into design parameters by replacing a global accuracy requirement with a local one: each bounded region of the carrier is formatted to a self-consistent lattice, and the relationships between regions are encoded in boundary markers. The consequences for carrier performance are specific and quantifiable: crosstalk margins within each axial group are determined by intra-group geometry; recovery from servo dropout is bounded by sub-volume dimensions; scalability to 6,000-layer disc bodies requires adding groups. The petabit-scale recording demonstrated by Zhao et al. (2024) and the five-dimensional mark multiplexing of Zijlstra et al. (2009) define what volumetric media can encode; the sub-volume architecture of Polshchikov (2025) defines the organizational principle that makes carriers containing such encodings navigable by practical read-write systems.

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