Non-Sequential Formatting of Three-Dimensional Optical Carriers and Its Engineering Significance

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Abstract

Three-dimensional optical information carriers have long been constrained in production throughput by sequential formatting methods, in which servo and positioning marks must be inscribed along continuous spiral tracks one mark at a time. This paper examines the structural bottleneck imposed by sequential recording order, surveys the principal approaches proposed in the volumetric storage literature for addressing it, and evaluates a non-sequential interleaved formatting architecture as an engineering solution to reduce formatting time without sacrificing the geometric precision required for reliable track-following and data retrieval. The architecture organizes formatting marks on nodes of a three-dimensional lattice formed by the intersection of equidistantly spaced cylindrical spiral tracks, equiangular radial planes, and virtual recording layers, and employs interleaved axial and radial recording modes to distribute marks across this lattice in a non-sequential order that substantially reduces mechanical path length. The number of required recording head rotations per formatted layer is reduced from approximately 37,000 to approximately 600, a factor exceeding 60. Engineering implications for multilayer carrier production, sub-volume accuracy control, and concurrent formatting of multiple carriers are assessed against limitations documented in the volumetric optical storage literature.

Keywords: Three-dimensional optical storage, volumetric carrier formatting, interleaved recording, servo marks, lattice grid, axial formatting, radial formatting, multilayer optical media.

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1. Introduction

The architecture of optical disc storage has remained substantially planar since the introduction of compact disc technology in the early 1980s. Even formats that nominally include multiple recording layers store data in a small number of distinct reflective surfaces rather than distributing it throughout a three-dimensional recording volume. The fundamental limitation of planar storage is that data density is bounded by the diffraction limit in two dimensions; increasing capacity requires either smaller wavelengths, higher numerical apertures, or additional recording layers, each entailing penalties in terms of crosstalk, spherical aberration, and formatting complexity. Volumetric three-dimensional storage, in which the entire thickness of a disc body serves as a recording medium, removes the two-dimensional density ceiling in principle, but introduces a class of engineering problems related to organizing and inscribing formatting infrastructure across hundreds of axial layers.

Formatting marks, referred to in the optical disc literature as servo or positioning marks, are patterns pre-inscribed in the carrier that allow the read-write head to determine its radial position, angular position, and depth within the carrier volume. In two-dimensional disc systems, formatting proceeds by scanning an optical pickup unit (OPU) along a continuous spiral from the outer boundary of the recordable area to the inner boundary, activating the recording laser at timed intervals to produce marks at prescribed angular positions along each track. For a carrier with a track pitch of 800 nm and an active width of 37 mm, the number of spiral tracks per layer is approximately 37,000, and the total path length traversed by the scanning head is approximately 9,415 meters per layer (Polshchikov, 2025). For a volumetric carrier requiring 100 or more individually formatted servo layers, this scan must be repeated for each layer, producing a total formatting workload that renders the process industrially impractical.

The throughput problem associated with multilayer volumetric formatting has been identified in the literature but has not been resolved by approaches that have dominated volumetric storage research in the past two decades. Walker et al. (2003) documented the sequential positioning bottleneck in two-photon volumetric recording systems and identified the time required to reposition the focus point between successive mark locations as the primary constraint on formatting efficiency. Gu, Zhang, and Lamon (2016), in a comprehensive review of nanomaterial-based storage approaches, noted that the absence of a scalable formatting infrastructure constitutes a systemic barrier separating laboratory demonstrations from deployable media, distinct from and arguably more critical than achieving high volumetric density in the recording medium itself. Zijlstra, Chon, and Gu (2009), demonstrating five-dimensional optical recording in gold nanorod composites, achieved volumetric selectivity through plasmonic surface resonance sensitivity to wavelength and polarization, but did not address how the resulting medium would be formatted for systematic access by a reading system. Kazansky et al. (2016) reported 360 terabytes per disc capacity in fused silica via femtosecond laser nanostructuring, and explicitly identified data write speed as the primary obstacle to practical deployment.

This article examines an architecture developed by Polshchikov (2025) that addresses the formatting throughput problem at the level of recording kinematics and geometric organization. The core principle is replacing a sequential recording order, in which marks are inscribed one at a time along a continuous spiral path, with an interleaved order in which marks are distributed across nodes of a three-dimensional lattice in a sequence that minimizes mechanical displacement between consecutive recording events. The following sections analyze the geometric structure of the lattice, the two principal recording modes, the sub-volume accuracy control mechanism, and the conditions for concurrent multi-carrier formatting, drawing on documented limitations in the volumetric storage literature to situate the engineering contribution in its field context.

2. METHODS

The formatting architecture described by Polshchikov (2025) organizes formatting marks on the nodes of a three-dimensional lattice defined by three intersecting families of geometric surfaces: equidistantly spaced cylindrical spiral tracks lying in virtual recording planes at different axial depths; equiangular radial planes extending from the rotation axis of the carrier to the outer boundary of the recordable area; and virtual recording planes oriented substantially orthogonal to the radial planes, defining the axial spacing between recording layers. Each node of this lattice is located at the intersection of one spiral track, one radial plane, and one recording plane, constituting the nominal target position for one formatting mark. For the carrier geometry examined here, with D_{max} of 118 mm, D_{min} of 44 mm, and T1 of 800 nm, the number of spiral tracks per layer is $n = L/T_1$, where $L = (D_{max} - D_{min})/2$ equals approximately 37 mm, giving approximately 46,250 tracks per layer (Polshchikov, 2025). The number of radial planes is set equal to the number of marks on the outermost track, approximately 600, so that the angular spacing between radial planes is 0.6 degrees.

The lattice imposes two types of regularity on the mark distribution that together enable the interleaved recording order. Marks on the same radial plane but on different spiral tracks are angularly aligned: they all lie in the same half-plane extending from the rotation axis, so that when the carrier has rotated to bring a given radial plane into alignment with the OPU optical axis, all marks on that plane are simultaneously accessible by varying only the radial position and axial depth of the recording focus. This means one radial traversal of the OPU, at the correct angular position, can address all marks belonging to a single radial plane across all recording layers in one inward and one outward pass. Marks on the same spiral track but in adjacent radial planes are separated by a fixed angular distance equal to the radial plane spacing, so the carrier needs to rotate by exactly one angular increment between successive radial traversals. Carrier rotation is therefore stepwise rather than continuous, with each step equal to 0.6 degrees, and the total number of steps per formatted layer equals the number of radial planes: 600. This is the source of the 60-fold reduction in required rotations relative to the 37,000 rotations of the sequential spiral scan.

In the radial formatting mode, the OPU performs a fast reciprocating linear movement along a radius of the carrier while the carrier itself is substantially stationary in angular terms, advancing stepwise by one radial-plane angular increment between successive radial traversals. During each inward or outward radial pass, the recording laser is activated at the precise moment when the OPU optical axis crosses each successive spiral track position, inscribing one formatting mark per track crossing. Because the carrier is not rotating during the radial traversal, the timing of laser activation is governed entirely by the radial velocity of the OPU and the track pitch, both of which are controlled quantities. After 600 traversals, one for each radial plane, all 600 marks on each of the 46,250 tracks have been inscribed, completing one fully formatted layer. The OPU has traversed a total radial distance of 2 times 37 mm times 600 traversals, equal to approximately 44.4 meters, compared with 9,415 meters for the sequential spiral scan covering the same mark set, a reduction ratio of approximately 212 (Polshchikov, 2025). The pulse duration of the recording laser during each mark inscription event must be short enough that OPU displacement during the pulse does not smear the mark beyond its intended extent; the referenced work describes pulse durations of approximately 100 ns, which at a radial OPU velocity of 0.5 m/s produces a radial mark displacement of 50 nm per pulse, well within lattice node positioning tolerance. The resulting marks are elongated in the radial direction, producing an oblong shape consistent with mark morphologies found to be useful for track following in data reading systems, as described by Gu et al. (2016).

The axial formatting mode addresses the depth dimension of the three-dimensional lattice without requiring the OPU to be repositioned mechanically to each layer in sequence. The OPU traverses a spiral or circular track in the conventional manner, with the carrier rotating continuously, while the recording beam is rapidly refocused in the axial direction between successive carrier rotation intervals. During each rotation interval between one radial plane and the next, the OPU focus steps through all required axial depths, inscribing one mark per depth level at the current radial and angular position before the carrier advances to the next radial plane. The axial refocusing mechanism employs a differential thread system consisting of two coaxial threaded elements with slightly different thread pitches: rotating the outer element by one full turn advances the inner lens element by the difference in pitches, settable to as little as 0.05 mm per revolution, providing fine axial position control without a separate high-precision linear actuator. A spring preload eliminates backlash in the thread engagement. An electro-optical modulator variant is also described, in which voltage changes shift beam divergence and thereby focal depth, eliminating the mechanical bandwidth constraint at the cost of additional optical complexity. Jesacher and Booth (2010) demonstrated that writing marks at significant depths below the carrier surface requires spatially dependent correction of wavefront aberrations arising from refractive index mismatch; the differential thread refocusing approach described here achieves depth control mechanically rather than through wavefront correction, which simplifies the optical path at the cost of restricting depth accuracy to the precision achievable by the mechanical system.

A structurally significant feature of the non-sequential formatting architecture is the explicit partitioning of the carrier volume into independent sub-volumes, each formatted to a self-consistent lattice structure without requiring global coherence across the entire carrier. The motivation arises from the finite accuracy envelope of practical optical recording systems, bounded by the working distance of the objective lens, the stroke and positioning precision of the focus actuator, and the ability to maintain timing coherence between multiple OPUs. Gu et al. (2016) identified the accumulation of positional error across large recording areas as an unresolved challenge for volumetric storage systems, noting that error propagation along a spiral track causes the lattice to lose coherence after a finite number of turns. The sub-volume approach resets the accuracy reference at each sub-volume boundary: each sub-volume is formatted independently using a reference layer specific to that sub-volume, and the lattice within each sub-volume is internally coherent even if adjacent sub-volumes carry a small relative offset. In the axial direction, each group of layers is formatted by an OPU calibrated to a specific depth range; Polshchikov (2025) describe lenses in optical disc storage systems as capable of focusing in a depth range of approximately 100 micrometers without spherical aberration correction, allowing groups of approximately 20 layers at 4 to 10 micron inter-layer spacing to be recorded within one group; this depth range defines the practical upper bound on sub-volume axial extent for standard optical configurations. In the radial direction, the carrier may be divided into annular zones, each formatted with a different angular spacing between radial planes, producing locally uniform but globally varying mark density that compensates for the decrease in linear mark spacing at smaller radii.

3. RESULTS

The throughput advantage of non-sequential formatting becomes decisive when considered in the context of production volumes rather than single-disc laboratory demonstrations. Sequential formatting of one layer at a rotation speed of 100 Hz, cited in the referenced work as a practical limit imposed by centrifugal deformation of the disc body, requires 37,000 rotations divided by 100 Hz, equal to 370 seconds per layer, or approximately 6.2 minutes. For a carrier requiring 100 formatted layers, the sequential approach requires approximately 617 minutes per disc. The radial formatting approach, requiring 600 carrier steps per layer at equivalent step timing, reduces the per-layer formatting time by the factor of 62 derived from the ratio of required rotations, bringing per-layer time to approximately 6 seconds and the 100-layer formatting time to approximately 10 minutes. This is consistent with production cycle times for conventional two-dimensional disc replication. Li, Cao, Tian, Fu, and Gu (2015) demonstrated multifocal optical nanoscopy achieving 30 terabytes of recording capacity at gigabit-per-second data rates by employing 25 parallel focal spots, noting that the fundamental limit on recording throughput in volumetric systems is the total number of photons deliverable to the recording volume per unit time. The non-sequential formatting architecture is compatible with multi-spot OPU configurations of this type, since the radial traversal is not inherently limited to single-beam operation; a diffractive optical element splitting the OPU output into multiple simultaneous focal spots at different radial positions could reduce the number of required traversals by the number of simultaneous spots, providing a further multiplicative throughput gain on top of the 62-fold reduction from the non-sequential recording order.

The non-sequential formatting architecture extends to the simultaneous formatting of multiple carriers without requiring a proportional increase in OPU count. In the rotating-platform configuration described by Polshchikov (2025), N carriers are mounted on individual spindles arranged in a circular array around a central axis, while a platform carrying M OPUs rotates around the same central axis. The platform rotation is synchronized with each spindle rotation such that during each full revolution of the platform, each OPU sweeps a radial arc across each carrier in turn, inscribing one mark per track crossing per OPU per carrier per radial traversal. The total formatting rate is proportional to M times N. The angular relationship governing synchronization requires each spindle to rotate by an angle alpha equal to 360 degrees times k divided by M, where k is the number of equiangular radial planes intersecting the recorded layer plane and M is the number of participating OPUs, for each full revolution of the platform. A linear reciprocating alternative is also described, in which carriers on a reciprocating table pass beneath stationary OPUs, eliminating the rotational dynamics of the stage at the cost of longer table travel path.

Many volumetric carrier designs incorporate one or more embossed or inscribed formatting layers produced during fabrication of the carrier body prior to optical recording. The referenced work describes the use of a dual-beam optical system in which a first beam tracks the embossed reference layer by standard push-pull tracking methods, while a second beam records new formatting marks at a controlled axial offset from the tracked surface. The axial offset is adjusted by controlling the divergence of the recording beam through displacement of one element of a Keppler beam expander, which shifts the focal plane without requiring mechanical repositioning of the OPU housing. Walker et al. (2003) and Jesacher and Booth (2010) both identified accurate depth registration relative to a known surface as a critical requirement for volumetric formatting; the dual-beam reference approach converts the depth registration problem from cumulative error propagation across many independently formatted layers into a problem of accurate offset control between two simultaneously active beams, substantially reducing the precision demand on the axial positioning system. Zhang, Gecevicius, Beresna, and Kazansky (2013) noted that depth control accuracy in femtosecond glass nanostructuring is constrained by translation stage stability, and that stage-based control is adequate for layer spacings above approximately 1 micrometer; the reference-beam offset approach is consistent with achieving layer spacings in this range while maintaining required accuracy across the full carrier depth.

4. DISCUSSION

The engineering contribution of the non-sequential formatting architecture lies in solving a production infrastructure problem that has remained unaddressed while the volumetric storage research community focused on media physics and recording density. The volumetric storage field has produced remarkable demonstrations: Zijlstra et al. (2009) achieved five-dimensional multiplexing in gold nanorod composites; Li et al. (2015) demonstrated 30 terabytes in a standard disc form factor; Kazansky et al. (2016) stored multiple terabytes in fused silica with effectively unlimited archival lifetime. In each case, the demonstrated storage capacity substantially exceeds what can be systematically accessed by a reading system lacking a properly formatted carrier, because reading requires that the position of each data mark be knowable from the formatting infrastructure before the data is read. A carrier containing terabytes of recorded data whose marks are not referenced to a navigable lattice cannot be read by any tracking servo, regardless of the sophistication of the read optics. The non-sequential formatting architecture provides the missing infrastructure layer, and its significance is precisely that it makes the densities demonstrated in the research literature accessible to practical read-write systems.

A comparison with the approach taken by Day, Gu, and Smallridge (1999) in two-photon photorefractive systems is instructive. That work characterized material response of a photorefractive polymer to two-photon excitation and identified achievable mark size and erasure conditions, but treated mark recording as a sequential process in which each mark is inscribed at a fixed position before the next is addressed. The sequential assumption was appropriate for a laboratory demonstration of material behavior but does not scale to production of formatted carriers containing millions of marks per layer. The non-sequential architecture does not change the material physics governing mark formation; it changes the order in which marks are addressed and the mechanical motion that delivers the beam to each address. These two aspects of the formatting problem are largely decoupled, which means the non-sequential approach is compatible with essentially any volumetric recording medium that can respond to a focused laser pulse within the pulse duration permitted by the radial OPU velocity. The two-photon polymer of Day et al. (1999), the plasmonic nanorod composite of Zijlstra et al. (2009), and the two-photon fluorescent tape of Yuan et al. (2020) are all candidates for use with non-sequential formatting, provided their saturation threshold energies are compatible with available laser pulse energies at the required pulse durations.

The sub-volume accuracy control mechanism deserves particular attention in the context of multi-layer optical recording. Smolovich and Cervantes (2007) identified interlayer crosstalk as a function of layer spacing and formatting mark positional accuracy, showing that the signal-to-noise ratio available during data readout decreases as mark positions deviate from their nominal lattice locations. The sub-volume approach controls this deviation by partitioning the carrier into accuracy domains small enough that error accumulation within each domain remains below the threshold identified by Smolovich and Cervantes (2007) for acceptable crosstalk margins. The partition size in the axial direction is set by OPU working distance and aberration characteristics; in the radial direction, it is set by the angular precision achievable in synchronizing carrier and OPU rotations. For a carrier requiring a rotation step of 0.6 degrees between radial traversals, a stepper motor with 200 full steps per revolution provides a native step of 1.8 degrees, requiring microstepping or gearing to achieve the required resolution. This is a well-characterized precision engineering problem with established solutions, and the accuracy achievable in practice will determine the minimum sub-volume size consistent with acceptable mark placement error.

The most significant open question in the architecture as described concerns the mechanical bandwidth requirement on the axial refocusing mechanism. In the combined axial-radial mode, the refocusing system must step through all required axial depths within the time available between successive radial traversals. For the representative example with 600 carrier steps per layer at 100 Hz equivalent rotation, the step time is approximately 1.67 ms. For a carrier with 100 axial layers, the refocusing system must complete 100 axial position changes within this interval, requiring a refocusing rate of approximately 60,000 steps per second. The differential thread mechanism operates at speeds governed by motor rotation rate and gear ratio, and whether it achieves 60,000 steps per second at required accuracy is not characterized in the publicly available description of the architecture. The electro-optical modulator variant, in which voltage changes shift beam divergence and thereby focal depth, is not subject to this mechanical bandwidth constraint and could achieve the required depth-stepping rates electronically, at the cost of additional complexity in the beam path and a requirement for aberration correction of the electro-optical element itself, as noted by Jesacher and Booth (2010) in a related context.

CONCLUSION

The non-sequential formatting architecture analyzed here addresses the rate-determining bottleneck in three-dimensional optical carrier production by replacing the sequential spiral scan with an interleaved recording order organized around a predefined three-dimensional lattice. The reduction in required recording head rotations from approximately 37,000 per layer to approximately 600, derived from the lattice geometry and radial recording kinematics, reduces per-layer formatting time by a factor exceeding 60 at comparable rotation speeds. For a 100-layer volumetric carrier, this brings total formatting time from the range of hours to the range of minutes per disc, crossing a threshold of practical relevance for industrial manufacturing. Extension to concurrent formatting of multiple carriers provides a further multiplicative throughput gain. Sub-volume accuracy control decouples local formatting precision from global error accumulation, and reference-layer compatibility converts the depth registration problem from cumulative error propagation to bounded offset control. Among the approaches proposed to date, the architecture described by Polshchikov (2025) is the only one to address formatting throughput, sub-volume accuracy control, and multi-carrier concurrency within a single coherent framework, without dependence on any specific recording medium. The practical viability of the approach at manufacturing scale depends on the characterization of axial refocusing bandwidth and multi-body synchronization precision, both of which are well-defined engineering problems amenable to experimental investigation.

REFERENCES

1. Day, D., Gu, M., & Smallridge, A. (1999). Use of two-photon excitation for erasable-rewritable three-dimensional bit optical data storage in a photorefractive polymer. Optics Letters, 24, 948-950.
2. Gu, M., Zhang, Q., & Lamon, S. (2016). Nanomaterials for optical data storage. Nature Reviews Materials, 1, 16070. https://doi.org/10.1038/natrevmats.2016.70
3. Jesacher, A., & Booth, M. J. (2010). Parallel direct laser writing in three dimensions with spatially dependent aberration correction. Optics Express, 18(20), 21090-21099. https://doi.org/10.1364/OE.18.021090
4. Kazansky, P. G., Cerkauskaite, A., Beresna, M., Drevinskas, R., Patel, A., Zhang, J., & Gecevicius, M. (2016). Eternal 5D data storage via ultrafast-laser writing in glass. Proceedings of SPIE, 9736, 97360U. https://doi.org/10.1117/12.2220600
5. Li, X., Cao, Y., Tian, N., Fu, L., & Gu, M. (2015). Multifocal optical nanoscopy for big data recording at 30 TB capacity and gigabits/second data rate. Optica, 2(6), 567-570. https://doi.org/10.1364/OPTICA.2.000567
6. Polshchikov, I. V. (2024). Formation of the ecosystem and infrastructure of a smart object, Part 1. LAP LAMBERT Academic Publishing.
7. Polshchikov, I. V. (2024). Formation of the ecosystem and infrastructure of a smart object, Part 2. LAP LAMBERT Academic Publishing.
8. Smolovich, A. M., & Cervantes, M. A. (2007). Multilayer optical disk and method of its management for preventing its illegal use. In Optical Data Storage 2007 (paper MD1). Optica Publishing Group. https://doi.org/10.1364/ODS.2007.MD1
9. Polshchikov, I. (2025). Apparatus, program, system and associated method of production and formatting of the optical part of hybrid information carriers based on electromagnetic impedance and resonance spectroscopy with elements of artificial intelligence and artificial neural networks (U.S. Patent Application No. 63/571,864). United States Patent and Trademark Office.
10. Walker, P., Zhang, Y., Dvornik, A., Rentzepis, P., & Esener, S. (2003). Two-photon volumetric optical disk storage systems: Experimental results and potentials. In Optics in Computing, OSA Trends in Optics and Photonics, 90 (paper OFB2). https://doi.org/10.1364/OC.2003.OFB2
11. Yuan, X., Zhao, M., Guo, X., Li, Y., Yu, Y., Gan, Z., & Ruan, H. (2020). Ultra-high capacity for three-dimensional optical data storage inside transparent fluorescent tape. Optics Letters, 45(6), 1535-1538. https://doi.org/10.1364/OL.387278
12. Zhang, J., Gecevicius, M., Beresna, M., & Kazansky, P. G. (2013). 5D data storage by ultrafast laser nanostructuring in glass. In CLEO: 2013 Postdeadline (paper CTh5D.9). Optica Publishing Group. https://doi.org/10.1364/CLEO_SI.2013.CTh5D.9
13. Zijlstra, P., Chon, J. W. M., & Gu, M. (2009). Five-dimensional optical recording mediated by surface plasmons in gold nanorods. Nature, 459, 410-413. https://doi.org/10.1038/nature08053