A Phase-Coherent Paradigm for Audio-Laser Synthesis

Mike Cassidy
mikecassidy0000@proton.me
Concordia University
Montreal, Canada

Kristian North
kristian.north@concordia.ca
Concordia University
Montreal, Canada

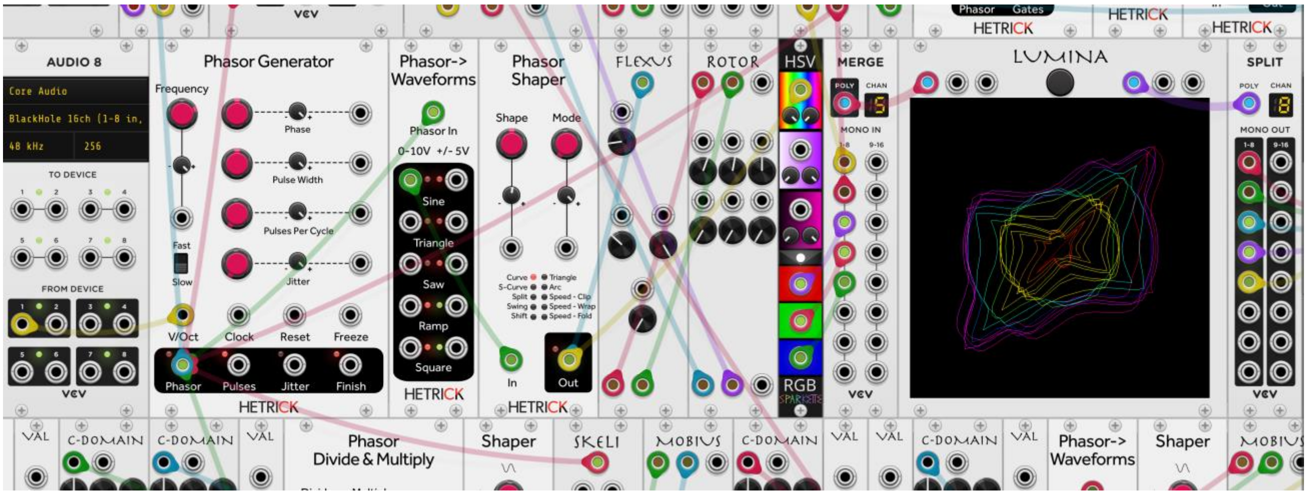

Figure 1: A patch on the *Phosphene* system in VCV Rack

Abstract

Audio–laser synthesis—where the same signals driving laser beam trajectory are simultaneously sonified—poses a distinct instrument design challenge: developing a unified signal architecture that encodes sound, motion, and colour without reducing the expressive range available to each modality. These requirements are well-suited to modular synthesis approaches, but scaling such systems beyond exploratory patches requires architectural principles for sustaining temporal stability across domains.

This paper presents a paradigm for audio–laser synthesis that maintains phase coherence throughout complex modular graphs. By establishing phase as a shared temporal reference for organising sonic, geometric, and colour domains, this paradigm enables systems to reliably scale in both size and complexity.

We demonstrate this approach through *Phosphene*, a VCV Rack plugin suite that extends audio-laser synthesis practice towards parity with contemporary modular synthesis. Through architectural description and performance-based validation, this work establishes design principles for modular audio-laser systems.

Keywords

Audio-laser synthesis, Modular synthesis, Signal Architecture, VCV Rack, Instrument design

1 Introduction

In audio–laser synthesis, the stereo voltages driving beam trajectory are simultaneously transduced into sound, a structural condition that binds spatial and sonic domains at the signal level. Geometry emerges specifically from the phase relationship between these two channels: the left and right signals drive horizontal (X) and vertical (Y) galvanometric deflection respectively, and it is the sub-harmonic phase differentials between them that transform flat Lissajous figures into volumetric, rotating forms. The art resides in sustaining and exploiting these inter-channel micro-variations as primary compositional material.

These same signals, however, are transduced by physically distinct systems — galvanometric mirrors, speakers, and laser diodes — each with different mechanical limits and response speeds. A phase relationship that reads as a coherent rotating form to the galvos may manifest differently across speakers and diodes responding to identical voltages. Visual projection is particularly sensitive: minor temporal imprecision causes stable geometric figures to collapse into incoherent motion, whereas audio perception is comparatively tolerant of the same deviations. Colour occupies a distinct position:

NIME '26, June 23–26, 2026, London, UK

controlled via direct electrical modulation of the laser diodes, it can share phase with the X/Y signals but is not structurally required to, leaving it at risk of becoming ornamental rather than an integrated dimension of the work.

As systems scale, both of these pressures compound: maintaining precise inter-channel phase relationships while accounting for the divergent transductive responses of each physical system grows increasingly difficult. Performances often default to simplicity to preserve visual stability, sacrificing the complex signal interactions across domains that define the medium's potential.

To address this, we present an architectural paradigm where phase functions as a shared temporal infrastructure for audio-laser synthesis. By grounding all sonic and visual behaviours to a unified global phasor, the performer can introduce calibrated deviation from phase alignment as deliberate compositional material rather than uncontrolled drift.

2 Related Work

Early explorations of signal-driven media established the possibility of generating geometric form directly from electric signals [1, 2, 3]. Subsequent laser-based practices extended this technique to sonifying the same signals driving the laser beam's trajectory [4], which has since seen revival within contemporary performance [5].

Current methodologies for laser synthesis have since branched into several distinct architectural lineages. Commercial systems such as Pangolin Beyond and Liberation adopt frame-based, timeline-oriented playback optimised mainly for visual sequencing rather than audio output [6, 7]. Hybrid audiovisual environments such as TouchDesigner allow audio-derived visual synthesis, but typically operate through translation layers that decouple sound from spatial signal continuity [8]. Other approaches prioritise the DAW ecosystem, with VST plugins like OsciRender and OsciStudio adding instrument-like capacities to standard production workflows [9, 10]. Finally, hardware instruments and custom software patches [11, 12, 13] enable audio-laser synthesis within a single device or environment, but often remain "closed" instruments rather than extensible modular systems.

Deluga's work on modular audio processes for vector graphic pattern design demonstrates the utility of phasor synchronisation for generating coherent geometric output [14]. However, this approach operates within a single visual domain, organising spatial geometry without extending to audio-laser coupling or chromatic control. Similarly, Holzer's Vector Synthesis Library [15] provides foundational examples for signal-driven geometry with extensibility for laser output, but Pure Data's encapsulated abstractions resist the active rewiring central to modular rack performance practice.

None of the approaches described above organise the signal architecture of audio-laser synthesis around a unified signal-level time base. Our approach draws specifically on the philosophy established by Wakefield and Taylor, who propose that sound and time can be organised at the sample level by treating the phasor as a shared temporal reference [16]. By applying this phasor-centric philosophy to the five-channel constraints of audio-laser synthesis, we formalise the phase-coherent paradigm presented in this paper, providing one approach to maintaining sonic and visual control across complex modular graphs at performance scale.

3 Phase as Temporal Infrastructure

The phasor as a shared temporal reference is an established primitive in both audio and video synthesis. In audio, its role as a phase accumulator underpins FM synthesis, phase-locked oscillator networks, and sample-accurate modulation. In analogue video synthesis, horizontal and vertical sync signals function as phasors that anchor all downstream processes to a common positional reference within each frame. The contribution of this paper is not the phasor itself, but its application to the specific five-channel constraint set of audio-laser synthesis, where sonic, geometric, and chromatic domains must remain coherent across complex modular graphs.

Within this architecture, phase operates in two structural roles. In the first, it functions as a synthesis driver: every point on a geometric figure corresponds to a determinate moment in the phase cycle, and every downstream process anchored to the same phasor is therefore anchored to a specific spatial position on that figure. Intentional deviation can be introduced as precise, calculable displacements from a known reference rather than as uncontrolled drift between independent processes. In the second role, the phasor functions as a spatial index: rather than constructing geometry sample by sample, a complete trajectory can be captured and stored, with a separate phasor traversing that stored material as a read pointer. This treats the shape as a whole Cartesian object, making available operations that real-time parametric synthesis cannot perform.

Together these roles operationalise Strange's observation that "the structure of electronic music depends upon the organisation of control relationships rather than upon the sounds themselves" [17]. The phasor provides the skeletal logic from which synchronisation, deliberate instability, and complex spatial operations are all equally possible within the same signal graph.

4 The Phosphene Framework

Phosphene instantiates these principles as a suite of over 40 VCV Rack modules, organised around what phase coherence makes available at each layer of the signal architecture.

At the foundation, treating phase as a shared resource rather than a property of individual oscillators establishes a specific kind of relational control. A global phasor becomes the single temporal reference for the entire graph, with clocks, gates, and envelope shapes derived as partitions of the same ramp and harmonic relationships between voices expressed as integer-ratio divisions rather than separately tuned oscillators. The HetrickCV library provides additional phase-based utilities that integrate naturally within this approach [18]. The practical result is a signal graph where complexity compounds without accumulating instability.

At the geometric layer, phase coherence makes two distinct modes of synthesis available. Source modules map the incoming phasor to coordinates via parametric equations, grounding every point on a trajectory to a determinate phase position. This makes downstream phase-locked processing spatially meaningful: amplitude modulation aligned to phase position introduces depth into the projected form; phase-locked filters, phasers, and flangers anchor spectral transformations to precise spatial locations on the figure; delay time clocked to the global phasor makes temporal repetitions function as spatial extensions of the source geometry rather than independent echoes. Where operations require knowledge of the complete shape, a buffer-based processing module records a full XY cycle on each phasor wrap and commits it to a buffer bank. A separate playback phasor then indexes into this stored material, enabling replication of the trajectory at configurable phase offsets, radial positions, or grid coordinates.

At the chromatic layer, phase coherence does not arrive structurally. Unlike X and Y, which inherit it through the physical constraint of two mirrors responding to two signals, the RGB channels carry no equivalent enforcement, so colour must be integrated deliberately. An HSV colouriser mapping the global phasor to hue makes spectral position a function of beam trajectory rather than an independent parameter. An intensity mapper converting modulation depth to RGB brightness makes signal transformation pressure visible as changes in beam intensity. Phase-locked blanking gates suppressing specific temporal segments of the RGB channels make discontinuous geometric forms possible while keeping chromatic behaviour synchronised with spatial trajectory.

5 Patch Examples

The following configurations demonstrate the application of phase-coherent principles across different dimensions of signal flow complexity.

5.1 Temporal Segmentation: Coordinate Sequencing

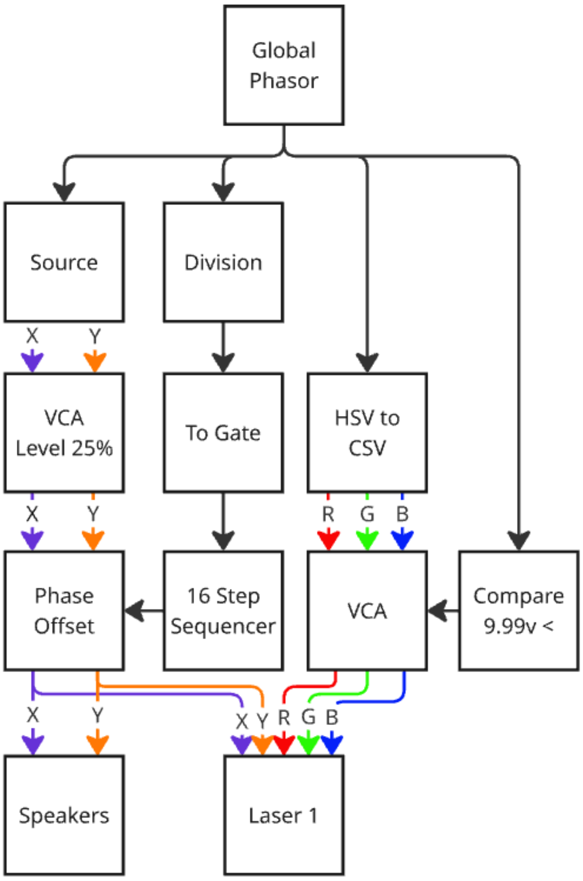

Figure 2: Coordinate Sequencing

Figure 2 demonstrates phase-locked coordinate sequencing. A global phasor serves as the fundamental frequency for a source module generating a square spiral. To position this trajectory into a grid, the spiral's amplitude is attenuated to occupy a single "cell" of the visual field. A phase division tracks a specified number of phasor cycles before gate-triggering discrete phase offsets set at each step of a 16-step sequencer. These offsets jump the trajectory to the next grid position. A comparator detects the edge of the divided phase to engage blanking of the RGB channels, suppressing the laser trajectory trace between cell jumps. When operated at high frequencies, this system achieves a form of signal multiplexing, where the persistence of vision allows the viewer to perceive a simultaneous grid of distinct, independent geometric figures generated from a single, continuous signal path.

5.2 Harmonic Integration: Multi-Voice Synthesis

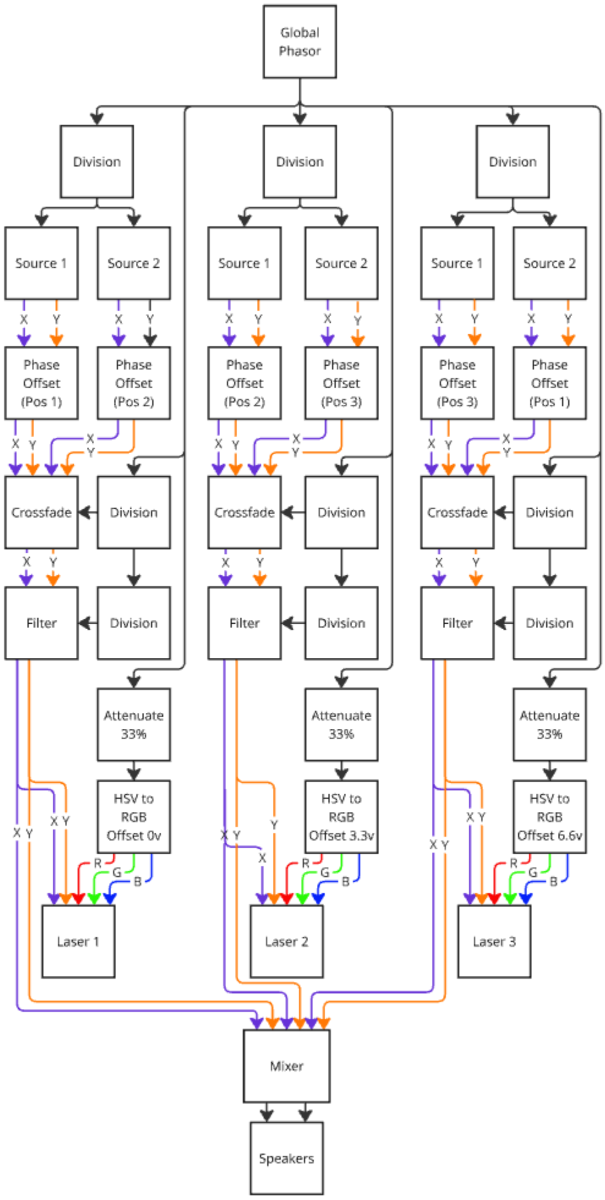

Figure 3: Multi-laser Fusion

This patch demonstrates multi-voice synthesis. A global phasor is distributed to three oscillator groups, each utilising a unique integer division to establish a stable triadic chordal structure (1:1, 3:2, 4:3). Each group contains a pair of contrasting source modules. By applying specific phase offsets to each module, the geometries are positioned to overlap with their counterparts in other groups, forming a unified, interlocking triadic structure. A secondary, low-frequency phasor division controls a cross-fader that morphs between these source types. Because every process is phase-locked, the three voices function as a single, structurally coherent entity.

6 Development and Performance

6.1 System Evolution

The design of *Phosphene* went through several architectural iterations, each addressing specific limitations in modularity and phase control. Initial exploration began with Holzer's Vector Synthesis library in Pure Data, but quickly migrated to Max/MSP to leverage gen~'s single-sample accuracy and the ability to write parametric equations directly in codebox. This environment also introduced the phasor-centric paradigm through the "Generating Sound and Organizing Time" package [16].

Early performances used DC-coupled MOTU audio interfaces, manually wired to ILDA connectors for laser control. As the system matured, we integrated a Helios Laser DAC, with signals routed through TouchDesigner solely for DAC connectivity. The patch was eventually ported to Max for Live to leverage Ableton's automation and clocking infrastructure. While this improved compositional control, the fixed instrument nature of a Max for Live device meant phase remained encapsulated within the device rather than freely routable as a modulation source across arbitrary signal paths. More fundamentally, the desired performance-scale complexity comprising many modules and connection points exceeded the structural capacity of the Max for Live architecture.

While the phase-coherent paradigm can be implemented in any environment capable of synchronous audio-rate signal processing, the migration to VCV Rack was motivated by specific performance requirements: phase needed to be freely routable across the signal graph rather than encapsulated within a device. VCV Rack's ecosystem of compatible third-party libraries also allows Phosphene modules to integrate directly with established modular sequencers and stochastic tools without custom translation logic, supporting the active rewiring that live performance requires.

6.2 Performance Practice

Figure 4: Still from an audio-laser performance designed with *Phosphene*

Phosphene has been used in 8 performances over the past year. Typical patch configurations range from 200 to 400 modules, approaching the CPU limits of standard performance hardware (e.g., Apple M1 MacBook Pro).

Configurations similar to those described in Section 5 have been deployed across these performances. The spatial sequencing approach (5.1) proved particularly effective for creating rhythmic, percussive structures, while the multi-voice architecture (5.2) allows for fluid movement between distinct melodic counterpoint and integrated, spectral clusters.

In practice, the architecture maintains stability under performance conditions despite VCV Rack's inherent timing limitations. The platform does not guarantee deterministic execution or single-sample precision, and modules may introduce variable latency depending on CPU load. However, these imperfections rarely manifest as perceptible instability because the architectural discipline provides sufficient coherence even when absolute timing precision is compromised.

7 Discussion

Audio-laser synthesis reveals a fundamental tension in multimodal instrument design: when separate domains are distinct transductions of the same signal, they inherit the physical limitations of each. In practice, this creates an environment where the rigorous demands of audio-laser synthesis often force a reduction of creative options.

The phase-coherent architecture presented here functions as a foundational leverage point against this restriction. By establishing phase as a global reference, the system externalises the responsibility for temporal coherence.

This shift enables the performer to operate at a higher level of abstraction. Instead of managing individual parameters to maintain stability, the artist designs control relationships and logic chains. Complex processes such as high-order feedback loops, conditional gate logic, and non-linear modulation can be chained together because the global phasor provides a constant temporal reference throughout.

8 Conclusion

This paper has formalised a phase-coherent paradigm for audio-laser synthesis in which a global phasor functions as shared temporal infrastructure across sonic, geometric, and chromatic domains. The central contribution is architectural: grounding all downstream processes to a single positional reference converts the asymmetric sensitivities of the medium from sources of instability into available compositional material. Phosphene instantiates this paradigm as a suite of over 40 VCV Rack modules, demonstrated across eight performances and validated through the patch configurations described in Section 5.

The paradigm addresses a specific scaling problem: as audio-laser systems grow in complexity, maintaining precise inter-channel phase relationships across physically distinct transducers becomes increasingly difficult to manage without a shared organisational reference. Phase coherence does not eliminate that difficulty but it raises the threshold at which complexity becomes unmanageable. Its application to other multimodal signal architectures, beyond audio-laser synthesis or VCV Rack, remains an open and worthwhile direction.

Ethical Standards

Research and performance involving laser projection carries inherent risks, including the potential for eye injury due to accidental exposure to laser radiation. In the development and performance of the systems described in this paper, we have ensured that all laser use adheres to applicable safety regulations and best practices, meeting or exceeding legal requirements. Appropriate precautions were taken to mitigate risk to performers, audiences, venue staff, and collaborators, including the use of certified hardware, controlled beam paths, and safety-conscious operating procedures.

Acknowledgments

We would like to thank Signal Culture and Hexagram for hosting residencies during which significant development of *Phosphene* took place, with special thanks to Jason and Debora Bernagozzi for their support. We also thank Alberto Novello and Simon Laroche for their guidance and mentorship during the early stages of this work.

References

[1] J. Whitney. *Digital Harmony: On the Complementarity of Music and Visual Art*. Byte Books, Peterborough, NH, 1980.

[2] B. Laposky. *Oscillons: Electronic Abstractions*. Sanford Museum, Cherokee, IA, 1953.

[3] M. E. Bute. *Abstronic*. Motion Picture, U.S.A., 1952.

[4] L. Cross. Audio/Video/Laser. In L. Austin, D. Kahn, and N. Gurusinghe, editors, *Source: Music of the Avant-Garde, 1966-1973*. University of California Press, Berkeley, 2011.

[5] D. Holzer, L. Aron, and A. Holzapfel. *Laser Phase Synthesis*. Proceedings of the International Conference on New Interfaces for Musical Expression (NIME), Mexico City, Mexico, 2023.

[6] Pangolin Laser Systems. Beyond Ultimate laser control software. https://pangolin.com, accessed Feb. 2026.

[7] Seb.ly Ltd. Liberation laser control software. https://liberationlaser.com, accessed Feb. 2026.

[8] Derivative. *TouchDesigner*. Software. Accessed January 2026. https://derivative.ca

[9] J. Fenderson and H. Raber. OsciStudio. Software for oscilloscope and laser music, accessed Feb. 2026.

[10] J. Ball. OsciRender. Lua-based vector synthesis platform, accessed Feb. 2026.

[11] Neon Captain. *Radiator* audio–laser hardware instrument. https://www.neoncaptain.com, accessed Feb. 2026.

[12] A. Novello and Manifold Research Centre. Lizajuice. Hardware audio–laser synthesiser. https://www.manifoldresearchcentre.com/lizajuice, accessed Feb. 2026.

[13] G. Özdemir, A. Çamcı, and A. G. Forbes. *PORTAL: An Audiovisual Laser Performance System*. Proceedings of the International Conference on New Interfaces for Musical Expression (NIME), Brisbane, Australia, 2016.

[14] C. Deluga. Modular Audio Processes for Vector Graphic Pattern Design. In Algorithmic Pattern Salon. Then Try This, 2023. https://doi.org/10.21428/108765d1.46efb0a3
[15] D. Holzer. *Vector Synthesis*. Software library for audiovisual synthesis, 2019. https://github.com/macumbista/vectorsynthesis
[16] G. Wakefield and G. Taylor. *Generating Sound & Organizing Time.* Cycling '74, San Francisco, CA, 2022.
[17] A. Strange. *Electronic Music: Systems, Techniques, and Controls*. Wm. C. Brown Company, Dubuque, IA, 1983.
[18] M. Hetrick. HetrickCV: VCV Rack module suite. https://github.com/mhetrick/hetrickcv, accessed Feb. 2026.