Persistence of Optical Interference Patterns Under Load

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We analyze the persistence of optical interference patterns as a structural property of constraint-defined equivalence classes under admissible perturbations, including measurement-induced load. Persistence is distinguished from robustness and stability and is shown to depend on invariance of relational structure rather than amplitude or visibility. Measurement enters exclusively as non-controlling load that constrains admissibility without selecting or interpreting structure.

I. PERSISTENCE OF OPTICAL INTERFERENCE PATTERNS UNDER LOAD

A. Introduction

Interference is among the most characteristic phenomena in optics, appearing across systems ranging from free-space diffraction to resonant cavities and integrated photonic structures. In many such systems, interference patterns are observed to persist despite perturbations to wavelength, boundary conditions, or measurement configuration. This persistence is often described informally as “stability” or “robustness,” but these terms conflate distinct physical notions and can obscure the underlying reasons why certain interference structures endure while others do not.

In this work, we address a more precise question: **which optical interference patterns persist, and under what conditions?** We treat persistence not as resistance to change in amplitude or visibility, but as **invariance of relational structure under admissible perturbations**. This distinction separates persistence from robustness (tolerance to noise) and from stability (dynamical return), neither of which is our focus. The contribution is conceptual and classificatory rather than explanatory or predictive.

Our analysis is confined strictly to optical and photonic systems. The aim is not to propose new optical phenomena, experimental protocols, or interpretations of measurement, but to clarify the conceptual status of persistence as a structural property distinct from robustness and dynamical stability. Measurement enters the analysis only as a physical interaction with the field that constrains admissibility, not as an act of interpretation, control, or selection. The goal is to characterize persistence as a property of constraint space in a canonical physical domain where interference and measurement-induced load are well characterized, without implying generality beyond this setting.

B. Conceptual Framework

1. *Interference as relational structure*

Optical interference patterns arise from the superposition of coherent fields and are defined by relations among phase, path length, and boundary conditions rather than by absolute field values.

2. *Constraints, admissibility, and perturbations*

We model an optical system by a set of constraints—boundary conditions, symmetries, and coherence requirements—that determine which field configurations are admissible.

In the present analysis, constraints are treated as descriptive elements of the modeling framework rather than as additional ontic entities. They summarize physically operative boundary, symmetry, and coherence conditions without reifying them as independent causes. Persistence is therefore a property of the constraint-defined model space under admissible perturbations, not a substance-like attribute of the optical field itself.

3. Persistence as equivalence-class invariance

An interference pattern persists if admissible perturbations map configurations within the same equivalence class defined by the governing constraints.

C. Formalization (Minimal)

1. Field representation

We consider coherent, monochromatic optical fields represented by

$$E(\mathbf{r},t) = \Re\{\psi(\mathbf{r})e^{-i\omega t}\}. \tag{1}$$

More generally,

$$\psi(\mathbf{r}) = \sum_k a_k\,\phi_k(\mathbf{r}). \tag{2}$$

2. Constraints and admissibility

Constraints are represented abstractly as

$$\mathcal{C}[\psi] = 0. \tag{3}$$

Examples include boundary, symmetry, and coherence constraints.

3. Equivalence classes and persistence

We define

$$\psi_1 \sim \psi_2 \quad \text{iff} \quad \mathcal{C}[\psi_1] = \mathcal{C}[\psi_2]. \tag{4}$$

In this framework, equivalence classes are descriptive constructs used to track constraint-invariant relational structure, rather than ontic entities or new physical degrees of freedom. Two field configurations are considered equivalent when they satisfy the same constraint relations, even if they differ in amplitude, visibility, or representational form. The equivalence relation is observer-independent but representation-relative, and is not intended to introduce a new mode decomposition, symmetry sector, or hidden variable structure.

4. Measurement as load

Observation is modeled as a non-unitary load map

$$\psi \mapsto \mathcal{L}[\psi], \tag{5}$$

for example,

$$\mathcal{L}[\psi](\mathbf{r}) = e^{-\gamma(\mathbf{r})}\psi(\mathbf{r}).$$

D. Measurement as Load (Back-Action)

Measurement enters exclusively as load, modifying admissibility and coherence without selecting or interpreting structure.

This use of "load" does not compete with or replace standard treatments of measurement back-action or decoherence. Rather, it functions as a classificatory abstraction that groups physically distinct interaction mechanisms according to their effect on admissibility and relational structure. The present framework does not model the dynamics of back-action; it diagnoses whether structural persistence is maintained or lost under such interactions.

E. Classes of Persistent Interference

1. *Boundary-enforced persistence*

In resonant cavities, waveguides, and bounded propagation domains, boundary conditions define the admissible modal structure. Standing-wave patterns and cavity modes persist under perturbations to excitation conditions or wavelength provided the boundary topology is unchanged. Such perturbations redistribute energy among admissible modes but do not alter the equivalence class defined by the boundary constraint.

2. *Symmetry-protected persistence*

Optical systems exhibiting spatial or modal symmetry admit interference patterns protected by group invariance. Perturbations that respect the symmetry preserve equivalence classes; persistence fails only under symmetry-breaking perturbations.

3. *Phase-rational interference*

Interference patterns defined by rational phase relationships persist under continuous parameter variation. Fringe extrema may shift, but relational structure remains invariant modulo 2π.

4. *Null and nodal structures*

Nulls, nodes, and phase singularities are defined by destructive interference. Their persistence is enforced by cancellation constraints and may exceed that of bright features.

F. Example: Two-Path Interferometer Under Load

Consider a two-path interferometer with phase difference $\Delta\phi$:

$$\psi(\mathbf{r}) = \psi_1(\mathbf{r}) + \psi_2(\mathbf{r})e^{i\Delta\phi}.$$

Equivalence classes are invariant under $\Delta\phi \mapsto \Delta\phi + 2\pi n$. Load may reduce visibility while relational persistence is maintained until coherence fails.

G. False Persistence and Over-Constrained Admissibility

Apparent persistence may arise when admissible perturbations are artificially restricted. Genuine persistence requires invariance under physically reasonable perturbations.

H. Indistinguishability Under Load

Distinct equivalence classes may become experimentally indistinguishable under sufficient measurement load. This collapse reflects observability limits rather than structural equivalence.

I. Implications for Optical Modeling

Persistence characterizes constraint-enforced invariance rather than optimization or stability. It complements coherence analyses while avoiding control-oriented interpretations.

J. Discussion

The present framework is adjacent to, but does not compete with, existing foundational accounts of interference and measurement. Decoherence-based treatments and measurement back-action models describe how environmental coupling suppresses coherence or alters dynamics, whereas the present analysis is concerned with the classification of constraint-invariant relational structure irrespective of interpretive stance. Similarly, structural and invariance-based approaches motivate the use of equivalence classes, but the framework here remains explicitly diagnostic and does not advance claims about ontology or interpretation.

In this respect, the contribution differs from gauge equivalence, symmetry protection, or topological invariance analyses, which explain why particular structures are preserved under specified transformations. The present work instead addresses whether relational structure remains invariant under physically admissible perturbations, without attributing the persistence to a specific symmetry, topology, or dynamical mechanism.

K. Conclusion

Persistent optical interference patterns are those whose relational structure is enforced by constraints and remains invariant under admissible perturbations, including measurement-induced load. Persistence is a property of constraint space, not of robustness or observation.

APPENDIX A

1. Illustrative Example (Non-Extending): Two-Path Optical Interferometer

This appendix provides a non-extending illustrative instantiation of the definitions in the main text and introduces no new claims or assumptions.

ERG is an external diagnostic vocabulary used here solely for descriptive convenience and is neither introduced nor defended in this paper.

Consider a simple two-path optical interferometer with a fixed source, a beam-splitting boundary, two propagation paths, and a recombination boundary. No assumptions are made about control, adaptation, or optimization; the configuration is static.

In ERG terms, the source generates a mediated field that propagates locally along both paths. The beam splitter and mirrors act as boundaries that shape admissible field configurations without encoding intent. Interaction occurs only through local field sampling at boundaries; no element has global knowledge of the system.

At recombination, the mediated fields superpose without negotiation. Depending on boundary conditions and path properties, the resulting structure may exhibit bounded persistence or dominant leakage. For example, if boundary conditions are compatible with a standing interference structure at the output, mediated structure persists locally despite ongoing loss. This corresponds to ERG stability: persistence of structure under bounded leakage.

Alternatively, if boundary conditions produce systematic cancellation at the recombination boundary, mediated structure fails to persist at that location. The dominant observable is interference nulling: transmitted structure is suppressed without invoking reflection dominance or geometric inadmissibility. Under ERG, this is classified as leakage via superposition cancellation, not as an error or failed choice.

If the boundaries instead couple strongly to unconfined propagation channels, mediated structure escapes the interferometer region. The dominant observable becomes outward radiation rather than local persistence. ERG classifies this as radiative leakage, again without implying mechanism, response optimization, or corrective action.

Crucially, in all cases the configuration remains geometrically admissible. Nothing in this example addresses which configurations are allowed to exist; that question belongs to geometric admissibility analysis. ERG diagnoses only whether mediated structure persists or leaks, and through which dominant pathway, given admissibility.

This example introduces no new primitives, mechanisms, or prescriptions. It serves only to illustrate how ERG terminology applies to a familiar optical setting and how stability and failure are diagnosed observationally rather than explained causally.