

Independence and Verification of Multimodal Authentication Features in Photocurable Inks and Coatings

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Statement of Significance

Two visible responses do not automatically constitute two independent authentication features. They may arise from one material variable, share one degradation pathway or fail together under one manufacturing deviation. ER-187 establishes a bounded framework for distinguishing multiple readout modes from genuinely independent evidence. It requires each mode to have a defined physical origin, acquisition protocol, decision rule and durability record, followed by explicit testing of cross-correlation and common-cause failure. The objective is verification of legitimate authentication performance, not disclosure of defeat methods.

Abstract

Security inks and labels can combine structural colour, fluorescence, photochromic switching and machine-readable patterns. Primary demonstrations show reflective and fluorescent information encoded in the same microstructured label, reversible visible/invisible information under alternating illumination, and fluorescent flexographic printing with measured optical and rub-resistance properties [1-3]. These studies establish feasible multimodal designs, but they do not by themselves prove that every observable response is statistically independent, stable across manufacture or robust throughout service. ER-187 defines a verification architecture that separates feature existence, readable contrast, information integrity, mode independence and lifecycle retention. It treats shared material state, shared excitation, reader cross-talk, registration error, ageing and batch variation as possible common causes. It does not prescribe universal thresholds, hidden keys, security patterns or attack procedures. A multimodal claim is accepted only when each mode is independently measurable, its decision rule is predeclared, dependence is quantified and the claimed operating envelope is supported by controlled production and durability evidence.

Keywords: security ink; anticounterfeiting; multimodal authentication; fluorescence; structural colour; photochromism; verification; common-cause failure

1. Scope and ownership

ER-187 owns independence and verification of multiple authentication modes in photocurable inks and coatings. Its scope includes defining modes, separating physical origins and readout channels, testing cross-correlation, controlling registration and manufacture, evaluating durability, and stating the evidence required for a bounded authentication claim.

Within the named sub-series *Radiation Curing Beyond Additive Manufacturing*, ER-187 examines the same photochemistry, oxygen-inhibition, attenuation, interfacial and qualification principles in security inks and coatings rather than only in printed layers. ER-187 addresses authentication-feature independence rather than the cure behaviour of those systems.

It does not re-author ER-056 photoluminescent, ER-087 magnetic, ER-078 colour or ER-007 electrical material-property reviews, which sit outside the ER-139–200 band and retain their respective scopes. It does not disclose covert patterns, secret keys, tolerances that would facilitate imitation, or procedures intended to

defeat an authentication system. Product security architecture, custody and operational response remain implementation responsibilities outside this public review.

The evidence core comprises three complete primary articles. Two demonstrate labels or inks with multiple optical states [1,2]. The third demonstrates a water-based fluorescent flexographic ink and evaluates printed optical and mechanical properties [3]. None is a universal qualification standard for photocurable security coatings.

2. A mode is not merely another image

An authentication mode is a defined chain from a physical state to a decision. It includes the excitation or observation condition, detector, acquisition geometry, signal processing, reference and acceptance rule. White-light reflection, ultraviolet-excited fluorescence and a reversible photochromic state may be separate modes, but only if their evidence chains are specified.

Qin et al. produced labels carrying different reflective and fluorescent information through microdroplets combining structural and fluorescent colour [1]. Li et al. produced reversible luminescence switching and printed patterns that changed between visible and invisible states under controlled optical stimuli [2]. These demonstrations show multiple observable states. They do not establish independence merely by counting outputs.

The first verification question is therefore not how many images appear. It is how many distinguishable physical-response and decision chains have been demonstrated.

3. Feature existence, readability and authentication are separate claims

A feature may exist spectroscopically but fail to be readable in the intended geometry. A pattern may be readable but insufficiently distinctive for authentication. A laboratory demonstration may authenticate a prepared specimen without establishing reproducible batch manufacture.

Verification should separate at least four claims:

1. the physical response exists under defined conditions;
2. the response can be acquired with the intended reader and geometry;
3. the acquired signal supports a predeclared decision rule;
4. the rule remains valid across legitimate production and the claimed service interval.

Evidence for one claim does not silently close the next. A bright fluorescent response, for example, is not automatically a controlled identity test.

4. Physical origin and channel separation

Each claimed mode should be traced to its dominant physical origin. Structural reflection can depend on periodic organisation and viewing geometry, fluorescence on absorption and radiative relaxation, and photochromic switching on a reversible molecular-state change. When different outputs derive from different structures, independence becomes plausible but still requires measurement.

In the microdroplet system of Qin et al., structural and fluorescent colours were deliberately combined while allowing different intact information to be observed in reflective and fluorescent states [1]. This is stronger evidence of channel separation than two colour coordinates derived from the same spectrum. Even so, both outputs remain embodied in the same label and can share manufacturing and environmental vulnerabilities.

The verification report should identify which material variable controls each response, which variables are shared, and which reader channels can cross-respond.

5. Independence is a measured relation

Two modes are independent only within a declared population and operating envelope. A useful test asks whether variation or failure in one mode predicts variation or failure in another after known production factors have been considered.

The study design should include repeated units from multiple batches, positions and production runs. For each mode it should record a continuous signal where possible, not only pass/fail. Dependence can then be examined through correlation, conditional error rates and shared-factor models. A low simple correlation is not sufficient when both responses depend nonlinearly on thickness, cure state or ageing.

Independence should not be claimed when the experiment contains too little variation to reveal dependence, when the same processed image generates both decisions, or when replicate readings of one specimen are treated as independent articles.

6. Orthogonality and common-cause failure

Orthogonal readout channels can reduce accidental correlation, but physical orthogonality does not eliminate common-cause failure. Layer thickness, pigment or taggant concentration, dispersion state, surface texture, cure conversion, oxygen inhibition, registration and substrate colour may influence more than one mode.

A controlled experiment should vary credible manufacturing and environmental factors within safe, legitimate bounds and determine whether modes move together. The aim is not to discover how to defeat a label. It is to identify process variables that could make legitimate features disappear together or produce correlated false decisions.

If one factor degrades all modes, the system may still be useful, but the public claim must describe multimodal readout rather than independent redundancy.

7. Stimulus-responsive modes require state control

Li et al. demonstrated a supramolecular coordination polyelectrolyte with reversible luminescence switching controlled by alternating optical stimulation, and used it as an ink for printed information patterns [2]. The work shows that a mode may depend on both material identity and controlled state history.

Verification of a switchable feature therefore requires definition of the starting state, stimulus band, exposure geometry, transition completion, recovery condition, cycle sequence and read delay. An apparent failure may be a state-preparation error rather than loss of identity. Conversely, a visible response after an uncontrolled stimulus cannot be interpreted without knowing the state path.

No switching dose or timing from one experimental system should be transferred to another formulation or reader.

8. Reader independence and cross-talk

Separate material responses can become coupled in the instrument. Detector spectral sensitivity, filters, illumination leakage, automatic exposure, white balance, polarisation, viewing angle and image-processing settings can cause one channel to influence another.

Reader verification should include mode-specific positive and negative controls, blank substrates, single-feature specimens where feasible, acquisition repeatability and a documented processing pipeline. A channel should be challenged with specimens that possess the other feature but lack the feature under test. This establishes whether the reader confuses channels without publishing sensitive decision thresholds.

Machine-readable patterns require additional control of focus, scale, contrast, geometric distortion and software version. Successful reading by one device is not universal reader compatibility.

9. Registration and information integrity

Multimodal labels may place different information in coincident, interleaved or spatially registered patterns. Qin et al. demonstrated distinct reflective and fluorescent messages within one programmed label [1]. Li et al. demonstrated information transformations associated with reversible optical switching [2]. These are information-level outputs, not only material-level spectra.

Verification should therefore assess whether each intended message is complete, whether unintended information leaks into another state, and whether spatial registration remains within the controlled design envelope. Misregistration can make two modes appear different while actually representing a manufacturing defect.

The public report may describe verification of information integrity without reproducing protected production artwork or covert spatial maps.

10. Printability is part of feature verification

An authentication material is not qualified as an ink merely because it is optically active. Printing requires controlled rheology, wetting, transfer, drying or curing, adhesion, resolution and compatibility with the equipment and substrate.

Li et al. demonstrated use of an aqueous responsive material in a commercial inkjet context [2]. Muthamma et al. formulated a water-based fluorescent flexographic ink, printed it on an ultraviolet-dull paper substrate, evaluated colour, optical density, fluorescence and rub resistance, and observed rapid room-temperature drying [3]. These studies show that print-process evidence can be integrated with optical evidence.

Their results remain process-specific. Inkjet and flexographic demonstrations do not establish vat-photopolymerisation, screen-printing or coating compatibility, and a water-based ink result does not qualify a photocurable formulation.

11. Cure state and film construction

For photocurable inks and coatings, cure state is part of the authentication system. Conversion, film thickness, oxygen inhibition, optical attenuation, dispersion and substrate interaction can alter both signal intensity and mechanical retention.

The verification plan should control formulation identity, lot, mixing history, deposition method, wet and cured thickness, exposure spectrum, irradiance mapping, thermal history and post-cure. A feature that passes only at one uncontrolled thickness or cure state cannot support a manufacturing claim.

Where the security material is not itself photocurable, ER-187 may use it as evidence for authentication logic but must not transfer its processing parameters to a radiation-curable ink or coating.

12. Durability is mode-specific and system-specific

Primary demonstrations include photostability, switching-cycle behaviour, storage observations and rub-resistance testing under their stated conditions [1-3]. These measurements show that different failure mechanisms matter. They do not establish a universal service life.

Durability verification should expose legitimate specimens to the claimed combinations of light, temperature, humidity, abrasion, chemicals, flexing and substrate ageing. Each mode must be read before, during and after exposure using the controlled reader. Testing only overall label appearance can miss failure of a covert channel.

A retained signal is not sufficient if its decision distribution overlaps the reject population after ageing. Lifecycle claims require both signal retention and decision-performance retention.

13. Batch, position and unit structure

Replicate scans of one printed patch measure reader repeatability, not manufacturing reproducibility. A defensible programme separates readings, positions, units, sheets or parts, print runs, ink batches and raw-material lots.

Sampling should represent edge and centre positions, startup and steady-state production, expected thickness variation and relevant substrate lots. Statistical analysis should preserve these population levels. Pooling nested observations as independent units understates uncertainty and can exaggerate apparent independence between modes.

Bridging a new lot requires evidence that the variables controlling every claimed mode remain inside the qualified envelope.

14. Decision architecture and error reporting

Each mode needs a predeclared decision output. The report should state the measured feature family, reference population, processing version, repeat rule and treatment of unreadable results. Sensitive numerical thresholds may be retained in controlled documentation rather than disclosed publicly.

ISO 22383:2020 provides the applicable framework for selecting and evaluating authentication solutions for material goods [4]. ER-187 cites that framework without importing any threshold, class, evaluation level or acceptance criterion.

System performance should distinguish false acceptance, false rejection and indeterminate outcomes. For multimodal decisions, the combination rule must be defined before testing. Requiring all modes, accepting any mode or applying a sequential rule produces different error structures.

Independence claims require joint results, not only separate accuracy figures. The report should show whether errors coincide more often than expected under the claimed model, while withholding operational details that would weaken security.

15. Change control and reverification

Reverification triggers include changes in taggant, resin, binder, solvent or water quality; raw-material lot; dispersion or mixing; printhead, plate or deposition method; film thickness; cure source; substrate; reader hardware; filters; illumination; camera settings; analysis software; protected artwork; packaging construction; and service environment.

Not every change requires complete requalification. A bridging study is acceptable when it measures the affected response paths and retains representative controls. A supplier statement or unchanged product name is not evidence that multimodal dependence remains unchanged.

If one mode changes, all shared variables and the joint decision rule should be reassessed.

16. Minimum verification record

The controlled record should identify:

1. the legitimate specimen population and manufacturing state;
2. each mode, physical origin and acquisition protocol;
3. reader hardware, configuration and processing version;
4. positive, negative, blank and single-feature controls;
5. unit, position, run, batch and lot structure;
6. mode-specific and joint decision results;
7. cross-talk, correlation and common-cause analysis;
8. durability exposures and post-exposure decisions;

9. deviations, indeterminate results and requalification triggers;

10. protected details retained outside the public report.

This record supports auditability without exposing secret patterns or defeat-relevant parameters.

17. Evidence limitations

The three primary studies demonstrate particular optical materials, label constructions and printing routes [1-3]. Two are not photocurable systems [1,2], and the third is a water-based flexographic ink [3]. They support the distinction between modes, states, information outputs and printed performance, but they do not directly qualify a photocurable commercial authentication coating.

The studies do not provide a universal statistical definition of authentication independence, universal reader thresholds or a complete production qualification protocol. ER-187 therefore presents an evidence architecture whose acceptance criteria must be established for the actual system.

No claim is made that combining more signals automatically increases security. Security benefit depends on distinct evidence, controlled manufacture, reader performance, lifecycle retention and protected implementation.

18. Conclusions

Multimodal authentication is not verified by displaying two colours or two images. Each mode must have a defined physical origin, acquisition chain and decision rule. The modes must then be evaluated for reader cross-talk, manufacturing correlation, common-cause failure and joint error behaviour.

Primary studies demonstrate feasible combinations of reflective and fluorescent information, reversible optical states and printed fluorescent performance [1-3]. Their value lies in showing how material state, structure, printing and reading interact. Their parameters and performance cannot be transferred universally.

The defensible claim is bounded: multiple authentication modes are independently useful only where each remains readable and discriminating, dependence is measured, shared causes are controlled, and durability is demonstrated across the legitimate production population.

Related Engineering Review boundaries

ER-187 owns independence and verification of multiple authentication modes in photocurable inks and coatings. ER-056 photoluminescent, ER-087 magnetic, ER-078 colour and ER-007 electrical material-property reviews sit outside the ER-139–200 band and retain their respective scopes. ER-196 retains surface-cure control for thin pigmented radiation-curable graphic inks. ER-187 does not disclose defeat methods, secret patterns or operational response procedures.

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Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. This review does not claim that any 3Dresyns ink, coating, label, reader or authentication system is qualified for a specific security application.

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Data availability

No new experimental dataset was generated for this review.