

Irreversible Microstructured Optical RH Threshold Indicator with a Binary Visual Readout

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Summary:

A passive optical relative humidity threshold indicator is presented for irreversible recording of selected humidity exceedance events. The system is based on a low-cost, humidity-responsive biopolymer film with functional additives selected with future application and biocompatibility requirements in mind. Exposure to the assigned humidity threshold triggers disappearance of a visible structural-optical response, which remains absent after return to the reference humidity. Representative threshold variants showed complete visual loss of diffraction after exposure to RH values of 60, 70 and 80 percent, while the diffractive response remained visible after exposure to the highest sub-threshold RH level tested under the applied exposure protocol. The transition was confirmed by reflected optical intensity measurements. The concept offers a simple, battery-free route toward passive humidity threshold labels.

Keywords: humidity sensor, optical sensor, threshold indicator, irreversible sensor, structural color

Background, Motivation and Objective

Relative humidity (RH) is a critical parameter in packaging, storage, logistics and environmental monitoring, especially when exposure above a defined RH limit can affect material or product stability. In many practical cases, continuous RH monitoring is not required; instead, a low-cost indicator providing direct information that a selected RH threshold has been reached is sufficient. Conventional electronic humidity sensors offer quantitative readout, but they require power supply, electronics and data acquisition. This creates a need for passive, single-use indicators capable of permanently recording RH exceedance events.

Optical humidity sensors based on changes in light transmission, reflection, refractive index, diffraction or structural color have attracted considerable attention due to their simple readout and potential for visual detection [1–4]. Photonic and structural-color humidity sensors typically translate water uptake into reversible spectral or color changes. In contrast, the present work explores a passive RH threshold indicator in which exposure to the assigned RH threshold produces an irreversible binary visual response based on the loss of a visible structural-optical signal.

The objective of this work was to demonstrate a dye-free optical prototype of an irreversible RH

threshold indicator operating in a binary readout mode. The proposed system is designed as a reader-free threshold label, where state 0 corresponds to a visible optical response and state 1 corresponds to its permanent disappearance after exposure to an assigned RH threshold.

Description of the New Method or System

The sensor consists of a humidity-responsive biopolymer-based film containing functional additives selected to support threshold activation, low-cost implementation and future application-oriented material requirements. The film carries a microstructured optical surface that produces a visible diffractive response in the initial state. Upon exposure to the assigned RH threshold, water uptake induces swelling and structural relaxation of the microstructured surface, leading to disappearance of the optical response. After return to the reference humidity, the response remains absent, confirming the irreversible character of the transition.

The readout principle is binary. State 0 corresponds to visible diffraction before activation, while state 1 corresponds to no visible diffraction after exposure to the assigned RH threshold. The indicator is therefore designed to record threshold exceedance rather than to reconstruct the full humidity-time profile. The visual response was additionally verified by monitoring the reflected optical intensity before exposure and after return to the reference humidity.

The operating principle of the indicator is schematically shown in Fig. 1. The initial state corresponds to a visible diffractive response, whereas exposure to the assigned RH threshold activates the system and leads to irreversible loss of the structural-optical signal.

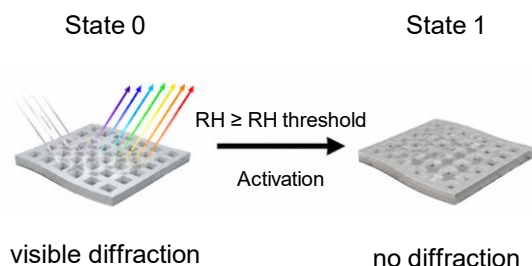


Fig. 1. Conceptual scheme of the irreversible micro-structured optical RH threshold indicator. State 0 corresponds to visible diffraction before activation. Exposure to RH at or above the assigned threshold leads to State 1, in which no visible diffraction is observed after return to reference RH.

The platform is expected to be adaptable to selected RH thresholds through material and structural tuning. Response-time control is also considered an important development parameter, but it is not addressed quantitatively in the present disclosure. The present contribution focuses on the sensing principle and functional performance; detailed formulation and fabrication parameters are not disclosed at this stage due to ongoing intellectual property protection.

Results

The response of selected threshold variants was evaluated by combining visual inspection with reflected optical intensity measurements. The initial state was defined by a clearly visible diffractive pattern. After exposure to target RH levels and return to the reference humidity, the final state was classified according to whether the diffractive pattern remained visible or disappeared.

Three representative threshold variants were selected for public presentation: 60, 70 and 80% RH. For each selected variant, the visible diffractive response was retained after exposure to the highest sub-threshold RH level tested under the applied protocol. In contrast, exposure to the assigned RH threshold resulted in complete disappearance of the visible optical response. The absence of the response was retained after return to the reference humidity, confirming irreversible activation under the applied test conditions.

The protocol included controlled RH exposure, RH stabilization and reflected-intensity monitoring, while detailed response-time mapping is considered a subject of ongoing work. The observed optical transition was accompanied by a strong loss of reflected intensity, confirming that

the visual change corresponded to degradation of the structural-optical response rather than to a temporary humidity-induced optical fluctuation.

Tab. 1: Binary RH-threshold response under the applied exposure protocol. V = visible diffraction; ND = no diffraction after return to reference RH.

Assigned RH [%]	Below threshold	At threshold
60	50% RH → V	60% RH → ND
70	60% RH → V	70% RH → ND
80	70% RH → V	80% RH → ND

The results confirm that humidity-induced loss of a microstructured optical response can be used as a passive memory of RH threshold exceedance. The system does not aim to continuously track RH changes or reconstruct humidity history, but to provide an irreversible 0–1 indication that a selected RH limit has been reached. Further work will focus on sharpening the transition window, improving below-threshold stability, evaluating response-time tuning and transferring the concept toward a practical low-cost label format. The dye-free prototype presented here may also serve as a platform for future integration with colorimetric components, if required by the target application.

References

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