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# A Universal Photonic Time–Temperature Indicator (TTI) with Programmable Irreversible Color Transitions for Smart Cold Chain Monitoring

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## Abstract

**Background and Objective** Maintaining strict temperature integrity across global cold chains is crucial for preserving the quality and safety of perishable foods, vaccines, and biopharmaceuticals(Charlton. K, 2016; Ahmed Edhirej et al, 2017). While conventional commercial TTIs provide irreversible tracking, they are often constrained by high manufacturing costs, fixed operational ranges, or complex chemical components that present migration risks in food safety applications. Conversely, previously explored photonic crystal-based indicators offer excellent visual properties but are almost exclusively reversible, returning to their original optical state upon cooling and failing to permanently record thermal abuse. This study introduces a novel, passive, non-toxic, and highly cost-effective TTI framework utilizing silicate photonic crystals integrated with polyethylene glycol (PEG) to deliver a definitive, tamper-proof, and irreversible optical alert system(Zhao, et al, 2022; Soltani Firouz M, et al, 2021).
**Methodology** The TTI device was fabricated as a multi-layer lamination comprising an optically responsive sensing layer—made from monodisperse silica photonic crystals coated onto a background-suppressing black Kraft paper substrate—integrated with a solid phase-change PEG thermal trigger film. Thermal programmability across a broad operational window (-20°C to +65°C) was engineered by strategically blending individual and binary mixtures of various molecular weight PEGs (PEG 200–4000). Structural, chemical, and optical transformations were thoroughly validated using Differential Scanning Calorimetry (DSC), Scanning Electron Microscopy (SEM), Powder X-ray Diffraction (XRD), UV-Vis spectrophotometry, and Photoluminescence (PL) analysis(Xin Zhang X, et al, 2022)..
**Results** DSC analysis confirmed tunable melting parameters (spanning -35°C to +70°C) governed by the specific PEG blend ratio. Upon reaching the designated activation threshold, the solid PEG film undergoes a phase transition and permanently infiltrates the porous silica network via capillary action. SEM imaging verified a distinct morphological shift from an initially porous texture to a smooth, uniform polymeric coating. This permanent infiltration replaces the air voids, decreasing the refractive index contrast and disrupting the photonic bandgap. Consequently, UV-Vis spectra revealed a major redshift in absorption peaks (from 663.95 nm to 1013.30 nm), translating into a highly noticeable macroscopic color change from a vibrant structural blue to a completely muted, dark hue. Response lag times demonstrate extreme flexibility, independently scaling from 3.0 to 10.1 minutes by altering the PEG film thickness (2.32 mm to 5.95 mm). Simulated real-time environmental trials successfully

validated reproducible, irreversible alerts at critical packaging thresholds of 8°C, 25°C, and 55°C.

**Conclusion and Significance** The developed system offers a scientifically robust, instrumentation-free solution that resolves the reversibility dilemma of traditional photonic crystal sensors using cheap, scalable, and entirely food-safe materials. By providing decoupled control over both threshold temperature and time-delay kinetics within a single, adaptable architectural design, this platform presents a highly accessible solution for smart labels to safeguard logistics networks in the food, pharmaceutical, and biotechnology sectors.

**Keywords:** Time-temperature indicator, photonic crystal, irreversible color change, supply chain tracking, intelligent packaging

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