Intelligent Laser-Based Sensor in the Mid-Infrared Region for Precise Trace Detection of Benzene

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Benzene exposure is linked to 40% of leukemia cases, making its detection at trace levels critical for public and environmental health. Existing sensors face limitations in sensitivity, selectivity, or portability. This research develops a mid-infrared laser-based sensor with a novel combination of three features: a quantum cascade laser that targets benzene’s strongest absorption peak (14.84 µm), a multi-pass cell to enhance sensitivity, and a machine learning model to identify benzene in complex mixtures. The mirrors of the multi-pass cell were aligned to maximize the optical path length of the laser and increase the laser-gas interaction. Gas mixtures were prepared with known benzene concentrations, along with interfering species such as CO2 and toluene, and their absorbance spectra were collected. The machine learning model was trained to mitigate interference and predict benzene concentrations from these spectra. The predicted values were compared against the known manometric concentrations to evaluate the sensor's accuracy. A 3D prototype of the sensor with a footprint of 30 × 50 cm was developed for real-world applications. The multi-pass cell extended the optical path length from 23 cm to 76 meters, enhancing sensitivity. Additionally, the model accurately predicted benzene concentrations, yielding an R^2 of 0.99, when compared to the known values. Using Allan deviation, the sensor demonstrated a minimum detection limit of 25 parts per trillion, the lowest reported for an optical benzene sensor. This sensor is promising for real-time monitoring in industrial and urban environments, helping prevent exposure above the 200 ppb safety threshold and supporting large-scale emissions control.

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