Preliminary Analysis of an Automated WGM Micro-Laser-Based Bio-Sensing System for Environmental Applications

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***Abstract*—This study presents a preliminary analysis of an automated bio-sensing platform based on whispering gallery mode (WGM) micro-lasers, with a focus on its applicability to smart urban environmental monitoring. The system employs 30μm-diameter polymeric micro-spheres functionalized with specific capture agents, and is capable of detecting molecular interactions by tracking resonance shifts in the optical emission spectrum. As a test case, the system was evaluated on human interferon gamma (IFN-γ) at concentrations ranging from 31.3 pg mL^{-1} to 500 pg mL^{-1}. Spectral features extracted from the emission data were used to train various machine learning classifiers. The Random Forest model achieved the best performance under a leave-one-out cross-validation protocol. Despite limitations related to dataset size and class imbalance, the system demonstrated the ability to discriminate between analyte concentrations. These findings suggest that WGM-based micro-laser sensors could be adapted for compact, high-sensitivity, and label-free detection of airborne or waterborne contaminants in smart city environments.**

***Index Terms*—smart cities, bio-sensing, classification, whispering gallery mode, micro-laser, pollutant**

I. Introduction

In the context of smart cities, the demand for compact and sensitive environmental monitoring has driven interest in micro-sensor technologies. Whispering Gallery Mode (WGM) resonators represent a promising solution due to their ability to detect minute changes in refractive index or cavity geometry by trapping light via total internal reflection in hollow micron-sized dielectric cavities [1]. This enables label-free sensing of airborne pollutants, pathogens, and chemical residues in urban air or water. Incorporating a gain medium like a fluorescent dye creates an active cavity supporting stimulated emission modulated by WGMs [2], [3]. Currently, resonance shifts in WGM sensors are detected manually, limiting real-time and long-term monitoring. To enable practical urban applications, automated and miniaturized systems are required. This work presents a preliminary analysis of an automated WGM micro-laser sensing platform, tested using human interferon-gamma (IFN-γ) as a target analyte. Although focused on bio-sensing, the system could be adapted for environmental monitoring in smart cities.

II. Experimental Setup

Whispering gallery mode (WGM) micro-lasers were used to detect human interferon gamma (IFN-γ) antigen in vitro. Polymeric dyed micro-spheres, 30 μm in diameter and functionalized with IFN-γ antibodies, were deposited on a microscope slide with an 8-well chamber. Each experiment used 3–5 beads, each acting as a microscopic sensor producing a well-defined emission signal sensitive to environmental changes. The dyed micro-spheres were optically pumped using an external green pulsed laser source operating at 532 nm to excite the whispering gallery modes. The fluorescent dye within the spheres absorbed the green light and emitted fluorescence in the red spectral range. Figure 1 shows a sketch of the experiment and a representative emission spectrum. Batches of 50 emission spectra were recorded continuously over approximately 3 hours prior to solvent evaporation. This approach enabled real-time monitoring of IFN-γ binding to the micro-spheres, evidenced by the progressive redshift of the spectral resonances. The experiments considered IFN-γ concentrations (C_{IFN}) of 500 pg mL^{-1}, 250 pg mL^{-1}, 125 pg mL^{-1}, 62.5 pg mL^{-1}, 31.3 pg mL^{-1}, and 0 pg mL^{-1}, corresponding to the bare buffer solution.

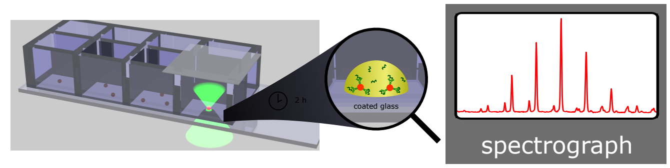

Fig. 1. Sketch of the experiment: micro-lasers are deposited on the glass and excited by an external green laser, the emission is recorded by a spectrograph following the progressive attachment of the antigens dispersed in solution on the surface of the functionalized beads.

III. Proposed Methodology

The analysis is based on a set of spectral measurements acquired from several beads. For each concentration, spectra were recorded over time after an initial baseline measurement. A set of features was extracted from these measurements to build a dataset for a classification task, where each class corresponds to a specific concentration level.

A. Feature Extraction

Feature extraction focused on the two most prominent spectral peaks over multiple time windows. To characterize the temporal evolution of these peaks, different features were extracted that quantify both positional and intensity-related changes over time. One of the features considered was the wavelength shift ($\Delta\lambda$), defined as the difference in peak position between the baseline and the final time window, as well as between the initial and final acquisitions. To better characterize this shift, the slope of a linear regression line fitted to the peak data points was computed for both the baseline–final and initial–final window pairs, capturing the rate and direction of spectral shift. Furthermore, intensity attenuation was quantified as the ratio of peak intensity over the same temporal intervals, offering a measure of signal decay. Figure 2 shows an example of the features extracted on a significant peak. This approach produced a set of twelve features per bead for each concentration level.

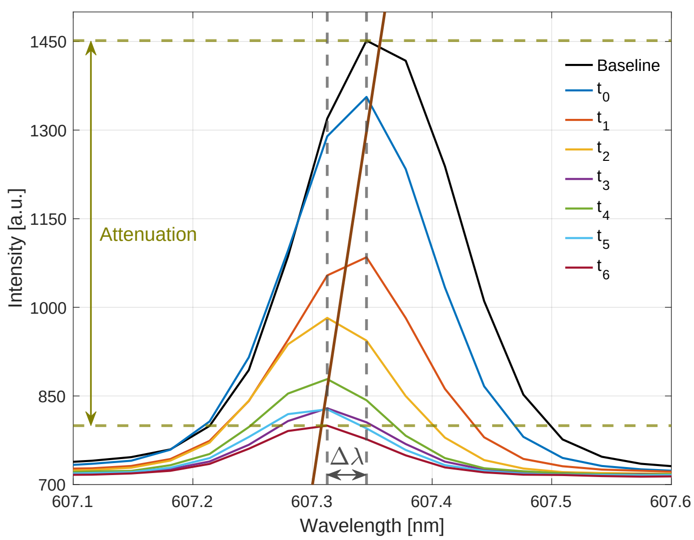

Fig. 2. Example of feature extraction: $\Delta\lambda$ (vertical dashed lines) and attenuation (olive dashed lines) from baseline to last acquisition window; regression line fitted to peak intensities (brown line).

B. Classification Analysis and Results

A classification study was conducted to evaluate the performance of various machine learning models in predicting concentration levels based on the extracted spectral features. Grid search was used to adjust the hyper-parameters of several classifiers, including AdaBoost, Decision Tree, K-Nearest Neighbors (K-NN), Logistic Regression, Random Forest, Support Vector Machine (SVM), XGBoost, and Multi-Layer Perceptron (MLP). Given the presence of a strong class imbalance in the dataset, the models struggled to generalize effectively. The evaluation protocol used a leave-one-out cross-validation strategy in which one bead per concentration level was selected as the test set, and the remaining beads were used for training. This configuration guaranteed that each sample was used to both training and testing, thus maximizing the exploitation of the dataset without excluding any instance. Among all the tested models, the Random Forest classifier demonstrated the best overall performance, achieving the highest values in both Matthews Correlation Coefficient (MCC) and F1-score. These metrics were chosen due to their suitability for evaluating classification tasks under class imbalance conditions. A confusion matrix is presented in Figure 3 to summarize the classification results.

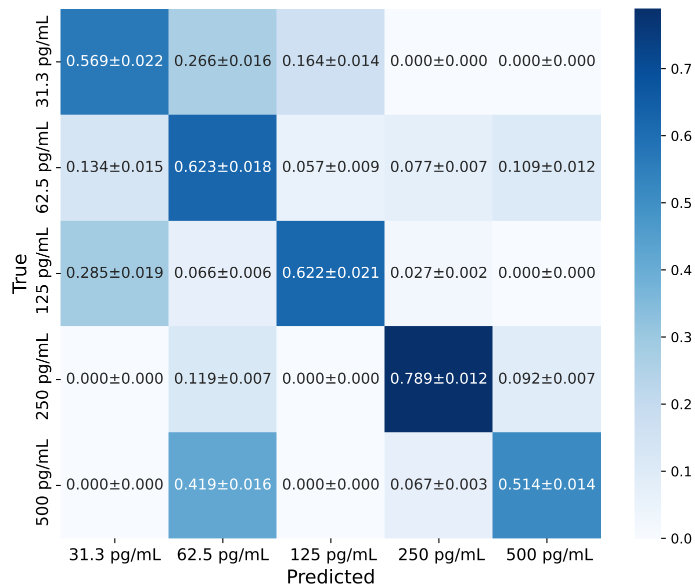

Fig. 3. Confusion matrix of Random Forest classifier.

The results show the system's capability to distinguish concentration levels, but classification was modest, likely due to class imbalance and limited data. These results should be considered preliminary, highlight the need for better-balanced datasets in future studies.

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