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RESEARCH

Edge-Plasmonic Nanoantenna Network for High-Throughput Glucose Profiling via Graph Neural Models

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Abstract

A hybrid plasmonic-GNN biosensing system was designed to allow rapid, precise and reliable quantification of glucose levels with a nano antenna optical biosensor. The paper is aimed at overcoming shortcomings of conventional plasmonic sensors, including low-concentration sensitivity, variability due to fabrication and spectral noise. It aimed to create a very sensitive nanoantenna system and design the best functional layers to bind the glucose molecules and couple the optical output with a powerful graph neural network that can derive the complex spectral-spatial patterns. The methodology combines several types of optimized gold nanoantennas (FDTD), 65 nm boronic-acid functional layer (hydrogel), CCD-based spectral interrogation, and preprocessing to advanced processing methods before GNN regression. The data showed a high correspondence between the simulated and experimental resonance performance that resonance at 780 nm (1.17% error), Q- factor of 41.3, and field enhancement of 27.9 times. The response of functionalized sensors was predictable and reversible with a 65 nm coating shift of 7.4 nm and a repeatability of 97.9% of the cycle. The GNN had high predictive accuracy, MAE of 0.12 mM, RMSE of 0.17 mM, and R^2 of 0.994. The cross-validation GOx assays exhibited $R^2 = 0.992$, which indicates clinical grade agreement and proves the platform to be well adapted to both continuous and point-of-care glucose monitoring.

Keywords Plasmonic nanoantenna · Glucose sensing · Au–graphene hybrid · Surface functionalization · Graph Neural Network · High-throughput optical readout · Electromagnetic hotspots · Biosensor stability.

Introduction

The general scientific issue with biomedical sensing and health management of metabolism is the quick, precise, and scalable monitoring of glucose. Plasmonic nanoantennas systems have been shown to have high potential in glucose sensing due to their ability to interpret optical reactions to modifications of refractive index at nanoscale through machine learning [1]. Plasmonic resonators of high figure of merit have also demonstrated that it is possible to weakly invasive, on-body glucose sensing using high-figure-of-merit plasmonic resonators with increased sensitivity and stability at physiological conditions [2]. Simultaneously, work done in flexible and densely packed sensor arrays facilitated by graph neural network (GNN) architectures has shown the benefits of spatial cognizant deep models when interacting with multi-channel sensor data with high-fidelity [3]. It has also been demonstrated that GNN-based sensor modeling can be used to maximize sensor placement, and also enhance communal signal understanding in

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a measurement network setting [4]. Plasmonic structures at the device-level with graphene, black phosphorus, and engineered perfect absorbers have demonstrated accurate resonance modulation applicable to biochemical detection biomolecular interactions of glucose-specific binding [5, 6]. The innovative nanoantena array configurations including hybrid square-horn and trapezoidal THz are now capable of providing field confinement and tunable optical response with enabling high throughput sensing applications [7, 8].

In the meantime the hydrogel-functionalized plasmonic nanoantennas have demonstrated selective and reversible glucose-responsive behavior, which is the primary criteria of biosensing reliability and repeatability [9]. Massively parallel plasmonic sensing of and spectrometer-free optical readout of nanoarray pixel arrays Large-scale integrated high-Q nanoantennas pixel arrays (VINPix) have demonstrated the feasibility of massively parallel optical readout and plasmonic sensing in small formats [10]. Also, super-radiative plasmonic nanoantenna biosensors have used high levels of scattering enhancement to detect sensitive molecules by optical measurements as simple or as visual [11]. Lastly, plasmonic fluor-enhanced antigen array devices have demonstrated that plasmonic architecture-based systems combined with new readout strategies can be utilized to develop powerful high-throughput biosensing systems that can be applied to complicated biochemical layers [12]. These advancements combine to inspire the design of an edge-plasmonic-based nanoantenna network with a graph neural network to make glucose profiling precise, rapid and of high throughput. In order to realize the objectives of coming up with a high-throughput, accurate and intelligent glucose sensing platform, the following specific objectives are established:

- **Design and Fabrication of Nanoantenna Network**
    ○ To prepare a highly-tuned glucose-induced refractive index biosensor based on the nanoarray of edge-factor plasmonic nanoantennas.
    ○ To investigate the optimization of optical field distribution by the choice of the material (gold, silver, graphene or hybrid structures) and geometry optimization.
- **Surface Functionalization of Glucose Specificity**
    ○ To incorporate selective functional layers (e.g. hydrogel or boronic acid), whereby glucose binding is reversible and reproducible.
    ○ To functionalize the thickness, and chemistry to achieve the maximization of functionalization of response and signal fidelity.
- **High-Throughput Measurement and Optical Readout**
    ○ To create an optical interrogation system that would be able to measure spectral responses of the entire nano antenna array together.
    ○ To achieve a high throughput data collection, which can be used with multiple samples or large assay areas.
- **Connection with Graph Neural Networks (GNNs)**
    ○ To assemble a graphical model of the nanoantenna network in which pixels would be the nodes, the spatial/functional correlations would be coded within the edges.
    ○ To create and train GNN models to analyze and interpret multi-pixels optical responses, and assign them to glucose concentrations.
    ○ To compare the performance of GNN with that of traditional regression or convolutional models in terms of accuracy, robustness and generalization.
- **System-Level Demonstration**
    ○ To improve the integration of the nanoantenna array, functionalization, optical readout, and GNN processing to form a single integrated platform.
    ○ To show fast, high-precision and low calibration requirements needed in laboratory, point-of-care/wearable glucose profiling.
- **Evaluating and Optimizing**
    ○ To measure performance of sensor: sensitivity, limit of detection, repeatability, and stability.
    ○ To streamline the system architecture to allow scalability and real-world implementation, comprising a high throughput and multiplexed sensing capability.

Recent advances in plasmonic biosensing have demonstrated the effectiveness of resonator-based architectures and hybrid material systems for highly sensitive biochemical detection. Metal–insulator–metal (MIM) ring resonator configurations have been shown to provide strong electromagnetic field confinement and high refractive-index sensitivity, enabling accurate detection of bacterial pathogens through resonance modulation and spectral shifts [38]. Multimode plasmonic ring resonator supercells have further enhanced sensing precision by exploiting multiple resonance channels, allowing reliable detection of subtle refractive-index variations platforms that had built-in machine learning showed a similar signal fidelity and glucose detection capabilities [24].

The multi-pixel plasmonic data spectral and spatial correlations were reasonably represented by the Graph Neural Network (GNN). The convergence of training was also fast and the amount of loss was minimal, which suggests strong learning and less overfitting [25]. Graph Attention Network (GAT) was found to be superior to traditional GCN models and this indicates the benefit of attention mechanisms in emphasizing significant spectral-spatial attributes [26]. The GNN had good generalization capacity to small resonance shifts and was able to identify small resonance shifts under low and high glucose concentrations, which are normally difficult to detect under a natural plasmonic sensor [27]. Bigger jumps at a high concentration were predicted reliably, and it is in line with the studies on ultrafast heating injection coreshell plasmonic devices which increase the signal concentration and temporal resolution [29].

The predictive accuracy was very good with a mean absolute error (MAE), equal to 0.12 mM [26], a RMSE, equal to 0.17 mM [27] and a R^2 that amounted to 0.994 [28]. These indicators are better than traditional plasmonic glucose [13]. The G CNN was also robust to simulated noisy situations, such as spectral noise [30], baseline drift [31], and pixel dropout [32] with little effect on the results. Plasmonic platforms with machine learning have also been shown to be resistant to these perturbations [33]. The fast carrier dynamics in plasmonics-based thin-film films is another viable support to the quick and accurate detection of combining nanophotonic designs with graph learning models [34].

Real-time performance with 4096-pixel nanoantenna network An actual real-time customization of more than 120,000 spectra/s was demonstrated with low inference latency [35]. The uniformity analysis has shown the similarity of responses throughout the array with a small variance [36]. Corrections based on GNN, also increased localized discrepancies, which guaranteed that glucose estimates created at all pixels were homogenous [37]. Similar multi-pixel plasmonic sensing systems have also highlighted the significance of monochromatic optical output and pixel-to-age error correction by the large-area measurements [35].

Compared to other commonly used glucose assays, such as enzymatic (GOx) and colorimetric, cross-validation of the novel glucose assay demonstrated a high level of correlations and low level of variation, indicating a level of clinical-grade specificity [13]. Gold silver core shell and fiber optic plasmonic sensors have reported similar reliability [14]. The combination between material design and advanced data analysis has been tested with results of highly reproducible, sensitive, and real-time glucose detection with the help of hybrid plasmonic sensors that have incorporated computational modeling [15]. Integrated plasmonic-GNN platform provides a scalable and throughput solution that can monitor continuous glucose, diagnostics at point of care and can be used in research [36].

Limitations

Despite the strong performance of the proposed plasmonic nanoantenna–GNN platform, several limitations remain. The reliance on electron-beam lithography may constrain large-scale, cost-effective manufacturing, and alternative fabrication approaches could introduce additional variability in antenna geometry and coupling. The experiments were performed under controlled laboratory conditions using prepared glucose solutions; thus, the influence of complex biological matrices, nonspecific adsorption, and long-term biofouling in real samples has not yet been fully assessed. Although the boronic-acid hydrogel layer showed high short-term repeatability, its long-term chemical and mechanical stability under continuous operation requires further validation. From a computational standpoint, the GNN depends on supervised calibration data and may require retraining to maintain accuracy under changing environmental conditions, sensor aging, or deployment-specific variations. Finally, the current system is limited to glucose sensing, and extension to multiplexed or multi-analyte detection will require additional optimization of functionalization strategies and graph-based learning models.

Conclusion

A very sensitive and powerful plasmonic glucose sensing platform in this research was created by combining accurately fabricated nanoantenna array with sophisticated Graph Neural Network (GNN)-based computation analysis. Nanoantenna architecture was found to be highly reproducible and stable to provide uniform plasmonic resonance and effective confinement of electromagnetic fields, which is important in reliable biochemical detection. The analysis of the various plasmonic materials showed the special benefits of better tunability of graphene with stability, and high field enhancement of gold, providing a good balance between the values of sensitivity, spectral fidelity and long-term operational stability.

Boric-acid hydrogel layers on surfaces were highly effective in functionalizing surfaces and enhancing specificity and reversible glucose binding in that order to enable rapid response and still preserve the structural integrity on repeat cycles. The optical readout system exhibited high signal fidelity and uniformity with a multi-pixel array which allowed it to demonstrate high-throughput monitoring with a compromise of accuracy. Combined with a GNN-based computational model, the predictive capabilities of the platform were additionally positively imprinted and were able to capture subtle spectral and spatial correlations and be resistant to environmental noise, baseline drift and sensor variability.

Clinical validity of the proposed system was tested by cross-validation with the standard glucose assays and demonstrated that it could be a useful tool to monitor glucose precisely and in real-time. All in all, high-throughput optical readout, surface functionalization, hybrid plasmonic materials combined with advanced nanofabrication, and intelligent data analysis creates a scalable, reliable, and flexible platform of on-going biochemical detection. This study forms the basis of further engineering of hybrid plasmonic biosensors, which has some potential to be used in the medical diagnostics fields, point-of-care diagnostic tools, and wearable sensing devices.

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Data Availability Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Ethics Approval and Consent to Participate No participation of humans takes place in this implementation process.

Human and Animal Rights No violation of Human and Animal Rights is involved.

Competing interests The authors declare no competing interests.

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