Design and Optimization of a Hybrid Graphene–Gold–Silver Terahertz Metasurface Biosensor for High-Sensitivity Sperm Detection with Machine Learning for Behavior Prediction

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Aims and scope

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Abstract

This study introduces a plasmonic-based sensor for sperm detection, integrating gold, graphene, and black phosphorus within a tailored multilayer structure. The sensor design consists of a silver-coated circular ring resonator (radius: 2–2.5 μm), a black phosphorus-coated square ring (7–8 μm), and four gold-coated circular resonators (each with a 2 μm radius) placed on a graphene-coated square platform. Electromagnetic simulations performed using COMSOL Multiphysics indicate optimal sensing performance within the 0.1–0.6 THz frequency range. The sensor demonstrates remarkable sensitivity of 5000 GHz per refractive index unit (RIU^{-1}), a figure of merit of 90.909 RIU^{-1}, and a detection limit of 0.02 RIU. It is capable of detecting sperm concentrations in a range of 17–197 million/mL, corresponding to refractive index variations from 1.33 to 1.3461. Furthermore, performance optimization through XGBoost machine learning achieved perfect prediction accuracy ($R^2 = 1.00$) across all test cases. This high-efficiency sensor marks a significant step forward in sperm detection technologies, with promising applications in male fertility assessment and reproductive medicine.