

Rapid Vaccine Screening and Component Analysis via a SERS Platform with Plasmonic Concentric Nanostructure Enhancers

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Summary:

This study presents a highly sensitive SERS platform based on plasmonic concentric nanostructures (PCN) for rapid, label-free analysis of the Spikevax mRNA vaccine. The nanorings generate strong hotspots, enabling clear identification of mRNA, lipid nanoparticles (LNPs), and excipients (e.g., sucrose, PEG) with high reproducibility, offering an efficient tool for vaccine quality control and stability monitoring.

Keywords: plasmonic concentric nanostructures (PCN), surface-enhanced Raman scattering (SERS), mRNA vaccine.

Background, Motivation and Objective

Vaccines are essential in modern healthcare, with mRNA vaccines transforming prevention during the COVID-19 pandemic [1-3]. Their clinical success relies on rigorous quality control (QC) to ensure the integrity and stability of complex mRNA–lipid nanoparticle (LNP) formulations, such as Moderna (Spikevax). However, conventional QC methods are often time-consuming, destructive, and require large sample volumes, limiting efficiency. To address these challenges, this study proposes a surface-enhanced Raman scattering (SERS) platform based on plasmonic concentric nanostructures. This approach enables rapid, label-free, and ultra-sensitive characterization using minimal, non-destructive samples. The generated electromagnetic hotspots amplify weak biomolecular signals, allowing precise identification of mRNA, LNPs, and excipients. This platform offers a powerful solution for real-time stability monitoring and scalable vaccine QC.

Description of the New Method or System

The core of the measurement system is based on PCN biosensors precisely fabricated using electron beam lithography (EBL). The circular grating defines a functional area of $1.2 \times 1.2 \text{ mm}^2$. The PCN biosensors are specifically designed with a linewidth of 400 nm and a pitch of 800 nm.

This optimized geometric architecture enables highly efficient excitation of surface plasmon polaritons (SPPs) under illumination [4-6]. As SPPs are generated and propagate along the concentric rings, they constructively interfere, significantly enhancing the localized interfacial electric field, particularly near the center of the structure. This strong electromagnetic confinement creates intense “hotspots,” which greatly amplify the SERS signals of target analytes, as shown in Figure 1. Consequently, this design markedly improves the optical sensing performance of the integrated system, providing ultrasensitive and reliable detection.

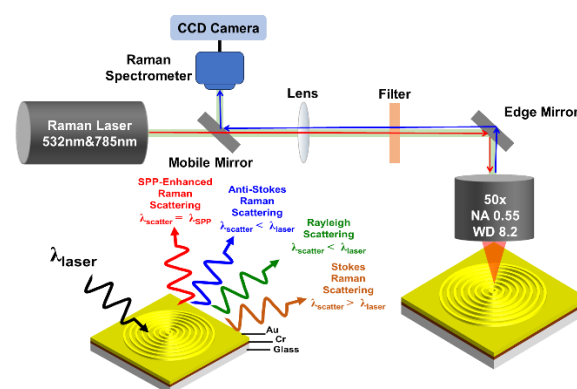


Fig. 1. A novel PCN biosensing platform designed for the highly sensitive detection of vaccines, enabling the accurate acquisition of amplified SERS signals.

Results

SERS spectroscopic analysis of the Moderna Spikevax COVID-19 vaccine was performed using the PCN-based biosensor across concentrations ranging from 2 to 200 $\mu\text{g/mL}$. Compared with a conventional Au film, the PCN structure exhibited an approximately 50-fold enhancement in Raman signal intensity (Lipids C-C) under optimized water conditions, as shown in Figure 2. Measurements were conducted using a 785 nm excitation laser with a power density of $0.0126 \text{ W}/\mu\text{m}^2$ (NA = 0.55). Overall, the results demonstrate that excitation wavelength, laser power, and measurement environment strongly influence SERS signal intensity and spectral features, highlighting the capability of the PCN platform for sensitive detection of vaccine biomolecular signatures under both dry and physiological-like conditions.

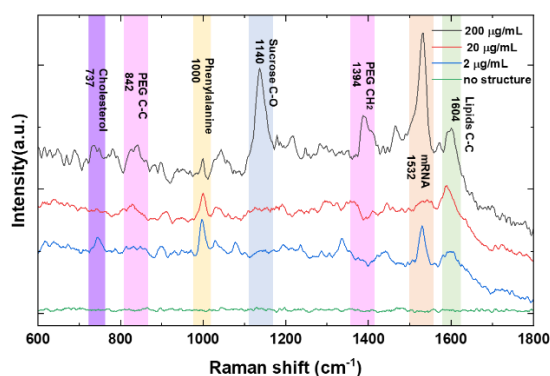


Fig. 2. SERS spectra of the Moderna (Spikevax) mRNA vaccine acquired using a PCN-based biosensor under varying measurement conditions.

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