Optoplasmonic Sensors

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Despite their astonishing breakthroughs in label-free optical sensing[1-3], optoplasmonic sensors (**Fig. 1**) have not yet reached their ultimate detection limits[4]. In fact, orders of magnitude improvement in sensitivity remains possible by optimising the sensor design and fabrication. I will review the impact of fabrication and self-assembly methods on obtaining ultimate sensitivity on optoplasmonic sensors.

I will discuss how fabrication impacts the following key parameters: I) *the time that light remains confined in the microcavity*. This cavity ring-down time τ is limited by scattering, absorption, and other losses mechanisms. The quality Q-factor characterises these losses. A high Q corresponds to a prolonged propagation of the light within the cavity: $\tau=Q/\omega$, where ω is angular frequency of the light. Q depends, among other factors, on the cavity geometry, the cavity material(s), surface roughness, and the light coupling method (a prism in the example shown in **Fig. 2A)**. By optimising Q and by fabricating the cavity volume V as small as possible (optimising for a high Q/V ratio) light completes multiple roundtrips in the microcavity as to enhance the detection sensitivity[4,5]. I will give examples for High Q/V sensors which can be fabricated from glass microspheres[2], silicon and silicon nitrate microrings, and silicon photonic crystals[6,7]. II) *The plasmonic near field enhancement*. Detection sensitivity enhances further via the plasmon resonances excited in the metal nanostructure attached to the microcavity. The sensitivity enhancement is in proportion to the local field enhancement E^2/E_0^2 at the sensing site. Optoplasmonic protein sensors can be fabricated from plasmonic nanostructures that provide the best compromise between loss and field confinement, meaning that geometries and materials properties of the plasmonic nanostructure can be chosen as to increase $\mathbf{Q/V\times E^2/E_0^2}$, with a proportional increase in detection sensitivity. Plasmonic nanostructure similar to the ones employed in tip-enhanced or surface enhanced Raman spectroscopy can be considered for this purpose. III) *The noise of the detection signal*. Detection limits in microcavity biosensing are often influenced by noise. The presence of a plasmonic nanostructure, which has a resonance condition of its own, coupled to the microcavity resonance will invoke mode mixing, creating a hybrid plasmonic-photonic mode. Optoplasmonic devices might be designed and fabricated to operate in the strong coupling regime[8,9], where the hybrid mode has two distinct spectral peaks in the signal, allowing for a self-referenced measurement, overcoming common mode noise. Furthermore, the signal-to-noise ratio of the frequency-shift in response to proteins will depend on the coupling strength which can be favourably increased on strongly-coupled plasmonic nanostructures[1,9,10].

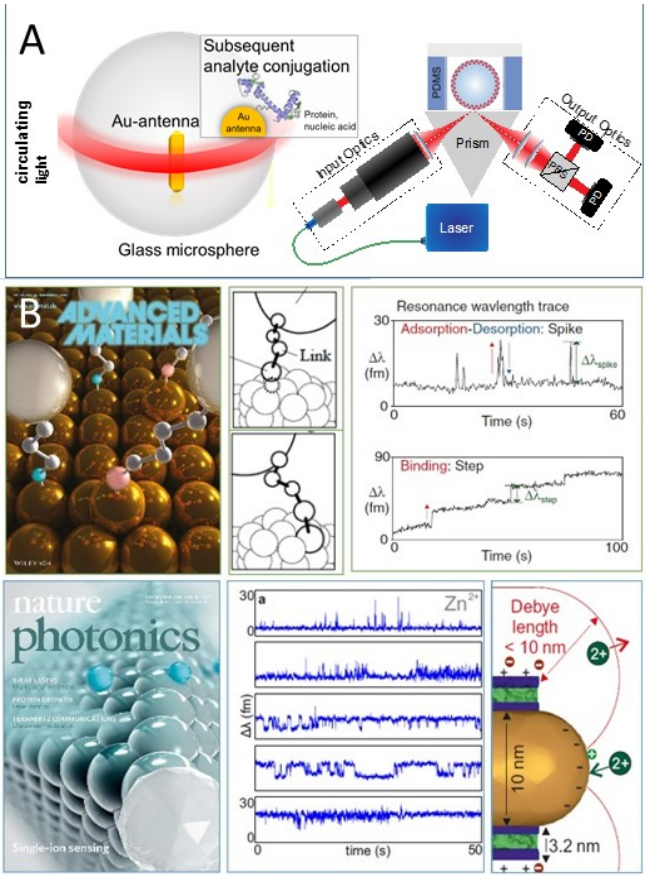

Fig. 1. **A**: Optoplasmonic single molecule sensor and system composed of a glass microsphere and an attached metal nanoparticle (Au-antenna). **B**: Examples for detection signals (resonance wavelength shifts $\Delta\lambda$) that were obtained from single molecules and single ions.

I will show design and fabrication approaches for three microcavity platforms, all of which promise similarly high detection sensitivities when operated in an aqueous environment: 1) glass **microspheres** that confine light by total internal reflection on whispering-gallery modes, WGMs[4], 2) equivalent silicon

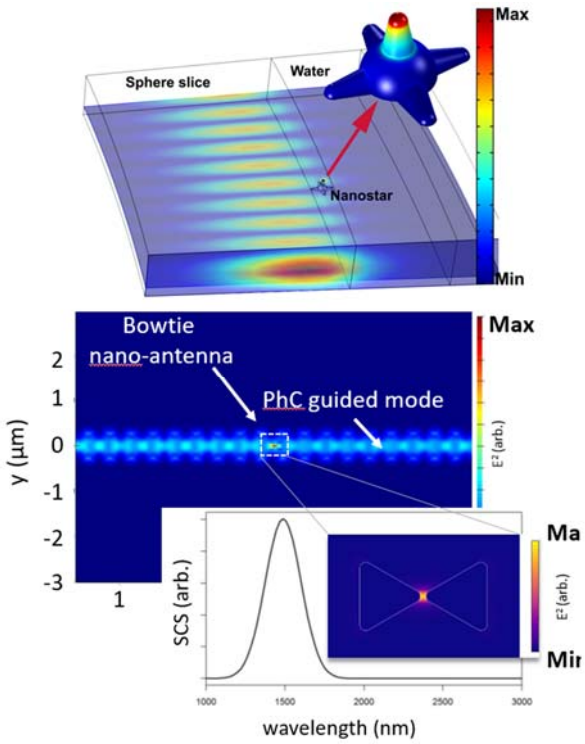

Fig. 2. Simulation of optical properties of optoplasmonic sensors. Top: nanostar coupled to a microsphere cavity. Bottom: Bow tie antenna coupled to a photonic crystal with **plasmon resonance at ~1500 nm wavelength** as shown by the simulated scattering spectra (SCS).

or silicon nitrate **ring resonators**, and 3) planar silicon **photonic crystal waveguides** that confine light by Anderson localisation[7]. These devices will exhibit resonance wavelengths in the visible or the near-infrared spectral regions suitable for plasmon coupling[11]. For example, bow tie antenna resonances can be tuned to match a silicon photonic crystal resonance even at near infrared wavelengths ~1500 nm. I will discuss fabrication advantages for all three platforms for optimised protein sensing, and I will show our approaches for theoretical modelling and numerical simulation of the modes relevant for sensing.

Accurate simulation of the field distributions aids the determination of optimized device parameters for sensing, visualisation, and spectroscopy of the biomolecule is reviewed. Mainly, the optimized shape and resonant properties of the nanoparticle are estimated for fabrication. A 3D finite element simulation of the coupled system of nanoparticle and microcavities is performed using COMSOL Multiphysics (v 5.3, COMSOL Inc., USA). **Fig. 2** depicts two of our 3D computational analyses showing intense light-matter interactions, one in a hybrid plasmonic microsphere resonator with fine geometric features of an interacting plasmonic nanostructure in close proximity.

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