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Nanophotonic device building blocks, such as optical nano/ microcavities and plasmic nanostructures, lie at the forefront of sensing and spectrometry of trace biological and chemical substances. A new class of nanophotonic architecture has emerged by combining optically resonant metal nanostructrues to enable detection at the nanostructure to enable detection at the nanoscale with extraordinary sensitivity.Initial demonstrations include single-molecule detection and even single-ion sensing.

The coupled photonic-plas-monic resonator system promises a leap forward in the nanoscale analysis of physical, chemical, and biological entities. These optoplasmonic sensor structures could be the centrepiece of miniaturised analytical laboratories, on a chip, with detection capabilities that are beyond the cur- rent state of the art. In this paper, we review this burgeon- ing field of optoplasmonic biosensors. We first focus on the state of the art in nanoplasmonic sensor structures, high quality factor optical microcavities, and photonic crystals separately before proceeding to an outline of the most recent advances in hybrid sensor systems.

Introduction:

Optical nano/microcavities are nano/microstructures that confine light for extended periods of time, resulting in optical resonances that can exhibit very narrow linewidths and high quality factors (i.e.*Q*-factors). The quality factor can be plainly expressed as $Q = \omega_{Res}\tau$ where ω_{Res} is the reso-nant angular frequency and τ is the ring-down lifetime.

Sensors that use these elements are subject to strong light- matter interactions as light encounters an analyte upon each cavity pass, thus elevating the sensitivity.

A whis-pering-gallery mode (WGM) cavity, such as a glass micro-sphere, is an example of this wherein light can be trapped due to total internal reflection. The number of round trips in such a cavity is limited by absorption, radiation, scattering, and other forms of loss. The *Q*-factor characterises these losses, as it also describes the fraction of energy lost per cycle. When continuously pumped, light will interfere with itself every round trip and set up an optical resonance with a Lorentzian line shape. In the simplest case, a collection of biomolecules binding to a microspherical cavity will result where σ is the surface density of bound biomolecules, α_{Ex} is the polarisability of biomolecules in excess of the external medium (e.g. water), n_s and n_m are, respectively the sphere and external medium refractive indices, and R is the microsphere radius . *Q*-factors of $10^{6–7}$ are common in biosensing applications and the aim is to in a resonant wavelength shift $\Delta\lambda = \lambda\sigma\alpha$ /[ε ($n^2 – n^2$)R.

optimise the Q while further reducing the mode volume $V = \int \varepsilon |E(r)|^2 dV / \max[\varepsilon |E(r)|^2]$, where ε is the permittivity and $E(r)$ is the position-dependent electric field. Plasmonic nanostructures and nanoparticles, on the other hand, confine light to nanoscale modal volumes V where even modest *Q*-factors (e.g. 10–100) of localised surface plasmon resonances (LSPRs) can result in very high near-field intensity enhancements. Such sensors have resonance shifts similar to those of optical nano/micro- cavities [5–7], where factors influencing the shift include the molecule's polarisibility, the modal volume, and the locally enhanced field at a "hot spot". The enhancement can strongly vary between plasmonic nanostructure geom- etries and, furthermore, explicit formulas for the resonance shift of plasmonic nanocavities by single nanoparticles or biomolecules have been derived .

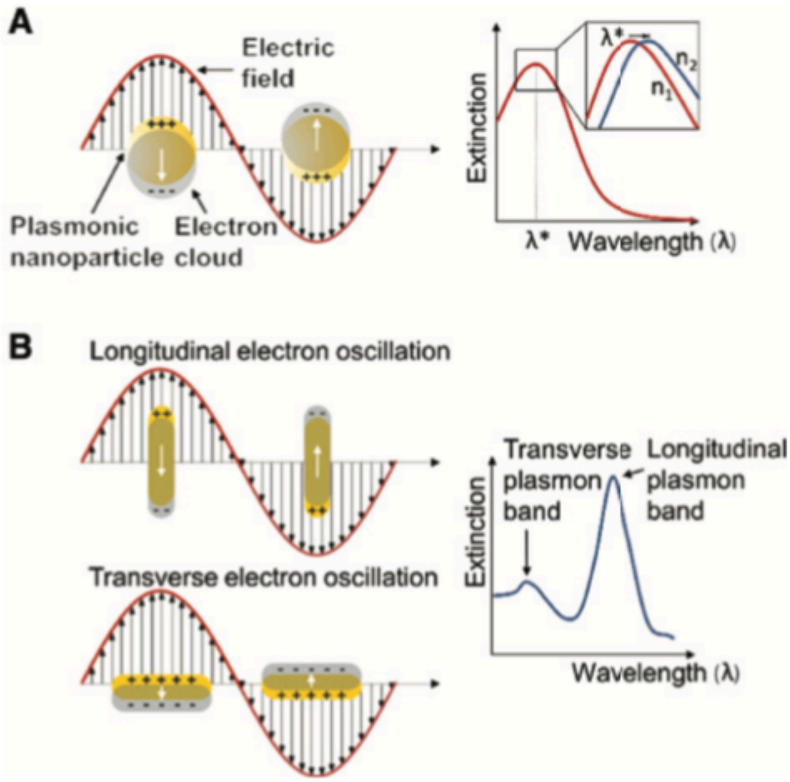
Sensing with high-*Q* optical nano/microcavities and plasmonic nanoparticles has been studied extensively for detecting physical, chemical, and biological entities. Speci- ficity in detection is often carried out with receptor mole- cules that establish analyte-specific interaction kinetics, traceable vis-à-vis perturbations in the optical or plasmonic resonances involved. Over the last decade, the underlying photonic and plasmonic sensing technologies have been dramatically improved. Most recently, both sensor structures have been combined into optoplasmonic systems as to simultaneously benefit from high *Q*-factors, small modal volumes, and extreme near-field enhancements. A com- promise between loss and field enhancement/confinement has to be sought in such a way as to viably increase *Q/V* and raise the field intensity at the sensing site. As such, pho- tonic-plasmonic hybdrisation lays the foundation for novel device physics, sensing modalities, and unprecedented detection limits, with demonstrations that include single- molecule and single-ion sensing.

This review is intended for the specialist in the areas of photonics or plasmonics who may not have been exposed to the emerging field of optoplasmonic sensor systems. These hybrid systems originate from three differ- ent fields: nanoplasmonics, high-*Q* WGM microcavities, and photonic crystals (PhCs). To convey the interdiscipli- narity, it is instructive to first review current advances in the underpinning technologies separately. After the state of the art for sensing with plasmonic nanostructures and high-*Q* optical WGM microcavities are covered, a com- prehensive review of the nascent field of optoplasmonic sensors follows. A discussion of one of the very promising means for integrating high-*Q* optical nano/microcavities and nanoplasmonic systems onto PhC devices follows. The most recent integration efforts for potential applications, e.g. analytical platforms, are highlighted.

The review closes with a discussion and outlook on the unique opportunities for sensing with plasmon-enhanced optical nano/ microcavities within a chip-scale package.

Plasmonic nanoparticles and nanostructures

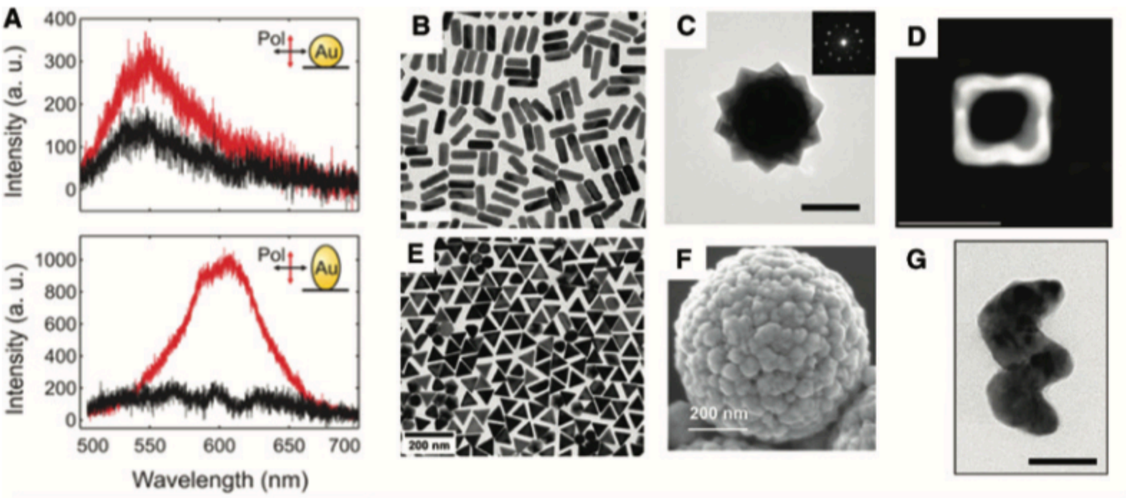
Plasmonic nanoparticles and nanostructures, with dimen- sions smaller than the wavelength of incident light, are well known to confine light and enhance its interaction with matter. In what is typically noble metal nanoparti- cles (e.g. gold, silver, palladium, etc.), an incident light beam induces a collective oscillation of conduction band electrons depending on the nanoparticle size, shape, and composition. These electron oscillations in the plasmonic nanostructures are confined to nanoscale volumes, depicted in Figure 1 and under what is termed a LSPR, leading to enhanced and highly localised electromagnetic fields that are several orders of magnitude stronger than the incident field – different from propagating surface plasmons on a planar, extended metallic surface . In view of this resonant behaviour, plasmonic nanoparticles and nanostructures act as independent sensor



in the extinction spectra of (A), in response to alterations in the refractive index of the medium containing the plasmonic nanoparticle. The nanorods of (B) show longitudinal and transverse plasmon bands corresponding to the electron oscillations along the long and short axes, respectively. Adapted and modified from.

elements that strongly improve surface plasmon-based sensing. The LSPR depends on the size and morphology of the nanoparticles and the electromagnetic field is concentrated in local features such as tips or edges, generating focused hot spots with sizes similar to single molecules (e.g. the nanorod's dipole pattern in Figure 1B).

LSPRs are particularly interesting for sensing appli- cations as the resonant frequency of the oscillating plas- mons depends on the changing dielectric properties of the local medium (i.e. effective refractive index change) within the decay length of the electromagnetic field . The change in chemical and molecular properties at the hot spots (for example, by adsorption of molecules) or in hybridised electromagnetic fields of nearby plasmonic nanoparticles can be sensitively measured by observing plasmon resonance variations. There is a shift in the resonant wavelength λ^* in response to an alteration in the refractive index of the medium containing the plasmonic substance (see the inset of Figure 1A) .



polarisation of the incident light. Specific shapes such as that in Figure 2G, however, lead to natural chirality . This enables LSPRs that are detectable via circular dichroism spectra, which are typically more feature-rich than extinction spectra and can be used for sensing more spectral signatures in complex biological systems with maximised sensitivity.

Coupling and bridging single nanoparticles and the creation of dimers with controlled gap distances establishes constructive coupling between plasmon resonances of adjacent nanoparticles and regions of intense local fields in the gaps between the nanoparti- cles. The local field enhancements facilitate single-mole- cule resolution in SERS and dark-field microscopy, where the gap width can be precisely set, e.g. by self-assembled monolayers of surface molecules or DNA-assisted coupling tethering of the nanoparticles.