APPLIED OPTICS

Nanoplasmonic sensing and detection

Enhanced optical fields in nanoplasmonic systems provide efficient sensing and detection

By **Mark I. Stockman**

Measuring minute amounts of chemical and biological objects in the environment and in living organisms is one of the most common and important tasks in chemistry, biology, medicine, environmental monitoring, transportation, homeland security, and defense. Although the existing methods of sensing and detection are numerous and powerful, they are not without shortcomings: insufficient sensitivity; long detection times; necessity for enzymatic, fluorescent, or radioactive labeling; high costs, and so on. Optical spectroscopic methods have the advantage of being fast, noncontact, and relatively inexpensive, but they are not necessarily sensitive enough.

Nanoplasmonics deals with optical phenomena localized at surfaces and interfaces of metals that are due to light-induced electronic excitations called surface plasmons (SPs). For a metal nanoparticle embedded in a dielectric, the SPs are oscillations of electric field and polarization localized in space. These are localized surface plasmons (LSPs), whose excitation frequencies depend mainly on the dielectric properties of the constituents and weakly depend on the system size. For extended systems, the SPs are electromagnetic waves, the so-called surface plasmon polaritons (SPPs), bound to the surfaces and interfaces and propagating along them (*1*, *2*).

The SPs are oscillations of dielectric polarization, which create opposite surface charges at the nanoscale, whose attraction supplies the restoring force necessary for any oscillations. Objects to be detected (for example, analyte) bind to the surface carrying SPs. This binding can be made chemically and immunologically specific by using corresponding antibodies linked to the surface. The result is a change of the permittivity of the dielectric adjacent to this surface and, thus, an increase in the dielectric screening that then reduces the restoring force for plasmonic oscillations and, hence, reduction of the LSP resonant frequency and the SPP propagation velocity. High sensitivity of the SP sensing is due to the fact that SPs are tightly localized at the surface and thus highly sensitive to its dielectric environment. The proximity of the object to be detected to the surface carrying SPs results in a shift in surface plasmon resonance peak—detectable with both high selectivity and high signal-to-noise ratio.

In biomedical research and applications, SPPs have been used for more than two decades (*3*, *4*). However, a problem is that the SPPs on flat surfaces propagate too slowly to be directly excited by laser light. To resolve this problem, most SPP sensors are based on the so-called Kretschmann geometry (*5*), which requires precise adjustment of the incidence angle of the probing radiation.

The observation of extraordinary transmission through a periodic array of nanoholes (*6*) is a foundation of a novel plasmonic detection method (*7*) (see the figure, panel A). External radiation is incident normally on a periodic array of nanoholes in a plasmonic metal (gold) nanofilm and excites SPPs when the period is a multiple of the SPP wavelength; these SPPs carry optical energy through the holes with a high efficiency. The surface of the holey array is functionalized by antibodies selectively binding to components (antigens) of the Ebola virus. The model virus in biologically relevant concentrations is delivered by microfluidics to the surface and binds to it, decreasing the SPP velocity. The measured resonant frequency shift is very pronounced, thus demonstrating detection of this highly contagious pathogen. Due to the absence of the moving parts, stability, and low weight, the corresponding device can be made handheld for field use.

In another example, detection of the Dengue fever antibodies (*8*) uses a SPP interferometer (see the figure, panel B). Although interferometric SPP sensing is already known (*4*), this approach represented a first study on real patients suffering from this

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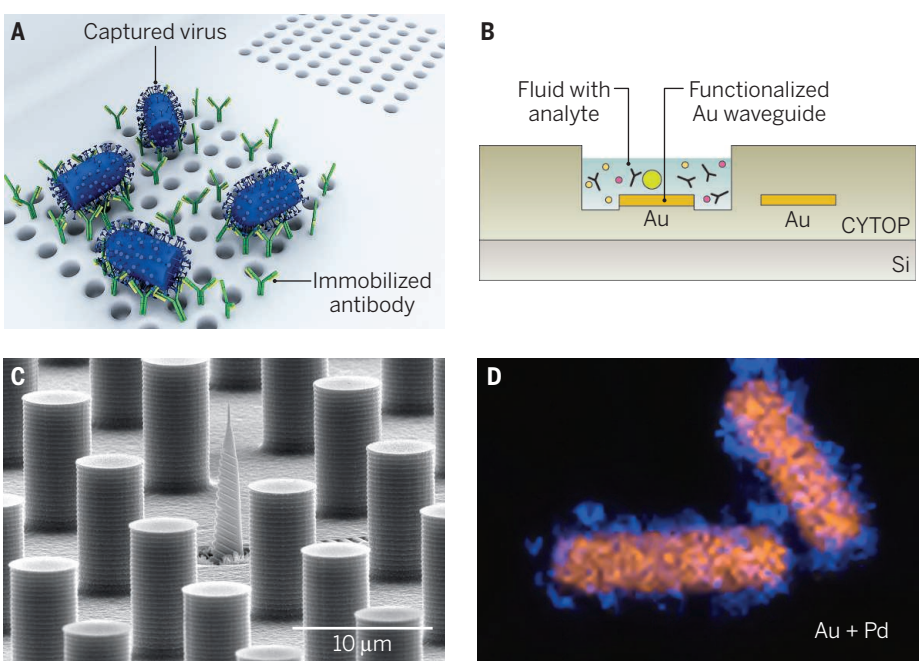
Capture and detection



Nanoplasmonic sensing and detection. Four nanoplasmonic detection experiments are presented. (**A**) Detection of Ebola-antigen–carrying virus [adapted from (*7*)]. (**B**) Detection of Dengue fever–specific antibodies from three actual patients [adapted from (*8*)]. (**C**) Detection of proteins and SERS identification of proteins in record-low femtomolar (10^{-15} mol/l) concentrations using adiabatic compression of surface plasmon polaritons and superhydrophobic delivery [adapted from (*10*)]. (**D**) Detection of hydrogen in the air in cycles of 10, 20, and 30 volume percent H_2, using gold nanorod-palladium nanospheres sensor-assembled employing DNA-directed assembly [adapted from (*12*)].

highly contagious and potentially deadly disease. The detection of the marker of the infection (antibodies to the virus in the blood) is so reliable that the detection efficiency is an order of magnitude better than for a "gold-standard" enzyme-linked immunosorbent assay (ELISA) method that is widely used in research and clinic.

One of the serious limitations of ultrasensitive detection comes not from plasmonics but from kinetics of the binding to the surfaces: The concentration of analyte should be on the order of or greater than ~5 to 20 fmol/l (*3*, *9*) for immunological reactions, which tends to make femtomolar to attomolar sensing and detection impossible. A novel approach (see the figure, panel C) overcomes this kinetic barrier and allows precise nanofocusing of the analyte at the active sensing center (*10*). This is achieved by using superhydrophobic coating of the shown micropillars. Surface-enhanced Raman scattering (SERS) detection is performed using the effect of adiabatic concentration of SPPs (*11*): Light is converted to SPPs by the grating in the metal nanocone shown in the center of this panel. The SPPs propagate to the tip, concentrating and creating a hot spot of optical near-field at the tip, exciting SERS in the analyte delivered to the tip due to super-hydrophobicity. The analyte, enzyme lysozyme, was delivered in a concentration of 1 fmol/l in a 160-nl drop, containing ~100 molecules overall. The subsequently detected Raman signature spectrum of lysozyme demonstrates a highly promising approach for ultrasensitive detection with chemical identification.

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One of the most important issues in clean energy is hydrogen technology, where a critical and yet unsolved problem is rapid and sensitive enough detection of hydrogen leaks. A single nanoparticle sensing for such detection (*12*) (see the figure, panel D) uses a gold nanorod covered with palladium nanospheres. Palladium is known to absorb hydrogen from air, which changes its dielectric properties and shifts the frequency of the LSP resonance of the nanorod. Such measurable shifts allow one to reliably and reversibly detect hydrogen in the air in concentrations relevant for hydrogen energy applications.

Plasmonic sensing of single proteins has been done with a hybrid photonic-plasmonic sensor consisting of a silica microsphere covered by a gold nanoshell (*13*). Here, the attachment of a single protein molecule to the nanoshell affects its plasmonic response and shifts the frequency of a whispering-gallery mode of the microsphere. More sensitive than the previous examples, such a shift affords the detection of single protein molecules.

A fundamentally novel principle, active plasmonic nanosensing, has recently been developed (*14*) based on spaser (plasmonic nanolaser) (*15*) as a metal nanoparticle surrounded by gain medium to generate coherent and intense local optical fields. The detection device consists of a nanoslab of semiconductor (CdS) separated by MgF_2 nanofilm from a silver surface. Optical pumping induces spasing on a mode localized mostly between the CdS and the silver surface. Exposure of such a spaser to 2 to 8 parts per billion concentration of vapor of explosive precursor dinitrotoluene causes an appreciable and reversible increase of the generated intensity—corresponding to one of the highest sensitivities of explosives sensors yet demonstrated. The examples discussed here demonstrate that plasmonics provides the fundamental basis and practical device designs that allow for the rapid sensing and detection of a wide range of important chemical and biological objects, such as hydrogen molecules, explosives vapors, protein molecules, and pathogenic viruses, and it can do so with unprecedented sensitivity and robustness. ■

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STRUCTURAL BIOLOGY

Mitoribosome oddities

The mitochondrial ribosome has evolved structural differences from its cytosolic counterpart

By **Roland Beckmann**[1] *and* **Johannes M. Herrmann**[2]

Eukaryotic cells contain two separate translation machineries for protein synthesis—one in the cytosol and one in mitochondria. This situation is attributable to the evolutionary history of eukaryotic cells, which originate from a merger of two formerly independent cells—the host cell and the bacterial endosymbiont—with each contributing a full-fledged protein synthesis system. However, during the past 1.5 billion years, the two translation machineries have evolved very differently. That of the host cell, which acts in the cytosol, synthesizes almost all cellular proteins, including most mitochondrial proteins. By contrast, in mitochondria—the descendants of the bacterial endosymbionts—ribosomes (mitoribosomes) are now highly specialized for the synthesis of a very small number (13 in humans) of membrane proteins that function in energy production. It has been assumed that mitoribosomes are still similar to those of bacteria. Now, advances in high-resolution cryo–electron microscopy have allowed fascinating insights into the molecular structure of mitoribosomes, as reported by Greber *et al.* (*1*) on page 303 of this issue and by Amunts *et al.* (*2*). It is clear that the mitoribosome differs dramatically from the "canonical" cytosolic ribosome of bacteria and eukaryotes (see the figure).

Ribosomes are composed of RNAs (so-called rRNAs) and around 70 to 100 different proteins (depending on the species). They are ribozymes, meaning that the enzymatic activity is exhibited by a catalytic RNA rather than by a protein. This is also true for mitoribosomes; however, in animals the RNA content is considerably smaller than observed for cytosolic ribosomes and is restricted to the catalytic core of the particle (*3*). Instead, all mitoribosomes exhibit greatly increased protein content: In mammalian cells, they contain 36 proteins that do not have homologs in bacteria and that

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