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Plasmonics in Nanomedicine: A Review

SS Verma*

Department of Physics, SLIET, India

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***Corresponding author:** SS Verma, Department of Physics, SLIET, Longowal, Sangrur, Punjab, India

Abstract

Plasmonics involves the confinement and manipulation of light at the nanoscale using surface plasmons and is making a tremendous impact in the field of life sciences, with applications in bioimaging, biosensing, and targeted delivery and externally-triggered locoregional therapy. In the present article, the latest developments in the area of plasmonics in nanomedicine are being presented.

Keywords: Optics; Photonics; Plasmonics; Nanoparticles; Nanomedicine; Surface plasmons

Abbreviations: IR: Infrared; UV: Ultraviolet; RF: Radiofrequency; DDA: Discrete Dipole Approximation; NIR: Near-Infrared Region; PDT: Photo Dynamic Therapy; PTT: Thermal PhotoTherapy; SERS: Surface-Enhanced Raman Scattering; LSPRs: Localized Surface Plasmon Resonances; MRI: Magnetic Resonance Imaging

Plasmonics and its Applications

The optical excitation of surface plasmons in metal nanoparticles leads to nanoscale spatial confinement of electromagnetic fields. The controlled electromagnetic fields while interacting with surface electrons can generate intense, localized thermal energy and large near-field optical forces and this interaction have led to the emerging field known as plasmonics.

Plasmonics is tremendously growing as a discipline at the interface between physics, chemistry and biology due to its promising applications in key areas such as energy, environment and health. Recent studies in plasmonics have made possible towards the recognition and development of novel optical materials and devices with applications particularly in biology and nanomedicine [1-28]. Taking the advantage of the coupling of light to charges like electrons in metals, plasmonics allows breaking the diffraction limit for the localization of light into sub-wavelength dimensions permitting strong field enhancements.

Plasmonics studies phenomena induced by and associated with surface plasmons - elementary polar excitations bound to surfaces and interfaces of good nanostructured metals. The field of plasmonics and metamaterials has attracted a great deal of interest in the last two decades, but despite the many fundamental breakthroughs and exciting science it has produced, it is yet to deliver on the initially targeted promising applications. Need is to examine the primary fundamental hurdles in the physics of plasmons that have been hampering practical applications and pin point first some of the promising areas in which the field can realistically deliver. Scientists [1-28] are keen to exploit the advantages that plasmonic nanoparticles of Nobel metals like gold and silver can offer. Recent research on the use of plasmonics properties of these nanoparticles depending on their size, wavelength and surrounding medium has revealed the possibility towards many beneficial and potential applications like biomedical, cancer treatment and plasmonic solar cells.

Biomedical Plasmonics

The interactions between atoms and surface plasmons can be categorized into three forms as: optical, thermal and mechanical. Within the scope of each type of interaction, there are applications of molecular plasmonics in biology and nanomedicine that involve sensing, spectral analysis, imaging, delivery, manipulation and heating of molecules, biomolecules or cells using plasmonic effects. Plasmonic nanoparticles due to their unique, tunable & functional properties can play an important role in biomedical applications as superior & optically stable bio-imaging agents which can be employed in bio-sensing devices for the early diagnosis of diseases.

They can also exhibit promising results in vivo as therapeutic agents. Nanoparticles that express more than one functionality are often more advantageous in several bio-applications. This has led to the synthesis of multifunctional plasmonic nanostructures that combine the attractive plasmonic properties with other functionalities such as magnetism, photoluminescence, dispersibility in aqueous solutions, and resistance to degradation. Multifunctional nanoparticles, thus, can be easily detected by multiple imaging techniques including magnetic resonance imaging (MRI) and fluorescence microscopy. Furthermore, their performance in diagnostics and therapy can be significantly improved due to early detection of diseases. The tunability of desired plasmonic properties of nanoparticles permits such hybrid nanoparticles to be employed in vivo as therapeutic agents that can actively target tumor sites and destroy them by external means which makes such bionanoprobes ideal candidates for non- or minimally invasive cancer treatments. With advanced design and engineering technologies to develop smart multifunctional nanomaterials with extraordinary properties will lead towards nano-based theranostics in the future.

Research in the field of plasmonics refers to the production and optical characterization of noble metal nanoparticles that differ in material, structure, shape, size and tunable plasmon resonance in the visible-near-infrared spectral region. Recent developments in the classification, production, electromagnetic simulation, and surface functionalization of plasmonic nanoparticles have opened up new possibilities for researchers. Plasmonic nanoparticles exhibiting properties like photostability makes them suitable for the use as bio-nanoprobes. Plasmonic nanoparticles scatter light strongly and therefore can be identified easily under dark-field illumination and in other sensing techniques which makes them suitable candidates to be used in various in-vitro biological applications.

Results of many projects have led to several potential biomedical applications such as optically stable bio-imaging agents, biosensor devices, and therapeutic agents. The realization of the importance and capability about plasmonics research has led scientists to work on combining the unique plasmonic properties with other operational qualities such as photoluminescence, dispersibility in aqueous solutions, resistance to degradation, and magnetism. Furthermore, the results also can be used to analyze how nanoparticles interact with cells. Gold and silver nanoparticles can be used as plasmonic biosensors for finding specific biomolecules and proteins that are useful for specific diseases. The recent simultaneous advances in synthesis, characterization, electromagnetic simulation, and surface fictionalization of plasmonic nanoparticles by bio specific molecular probes have led to a perfect publication storm in discoveries and potential biomedical applications of plasmon-resonant nanoparticle bioconjugates. Plasmonic bioconjugates have applications to such fields as homogeneous and solid-phase assays, biomedical sensing and imaging, biodistribution and toxicity aspects, drug delivery and plasmonic photothermal therapy.

Current Status

An integrated approach is applied in order to improve plasmonic therapy composed of nanomaterial optimization and the development of a theory for selective radiation Nano photo thermolysis of abnormal biological cells with gold nanoparticles and self-assembled nanoclusters. The different studies take into account the radiation-induced linear and nonlinear synergistic effects in biological cells containing nanostructures, with focus on optical, thermal, bubble formation, and nanoparticle explosion phenomena. The main medical applications are based on the principle of making use of localized surface plasmon resonances (LSPRs) peaks for their broadening, shifting, and height displayed by metal nanoparticles under different conditions. Therefore, different diagnostic methods based on selective nanoparticle aggregation (plasmon coupling), LSPR shifts, and surface-enhanced spectroscopies (surface-enhanced Raman scattering (SERS) in particular) are being developed.

Gold nanoparticles (Au-NPs) due to their plasmon resonance concentrate incident light in an extremely small volume on their surface. In nanohybrid structures (Au-NP/molecular adsorbate or semiconductor NP), this nanoantenna effect is used to enhance several kinds of linear and non-linear phenomena. The confinement of the electromagnetic field around colloidal NPs (crystalline and not rough) is stronger than that of NPs made by nanolithography. The relaxation of the plasmon occurs according to ultra-fast competitive relaxation pathways, the relative importance of which depends on the morphology of the nanoparticle, its surrounding environment and the irradiation mode. Thus, AuNPs can behave as nano-sources of light, heat or hot carriers and their morphology is a key parameter for this. Au-NPs also have high potential as contrast agents for medical imaging: photoacoustic imaging, dark field scattering, multi-photonic luminescence, high frequency ultrasound, quantitative phase contrast, or computed tomography. In the field of therapy, the generation of heat (Thermal PhotoTherapy, PTT) and more recently of R.O.S. (reactive oxygen species) from Au-NPs alone is an original way but still little explored to treat tumors, especially in the absence of oxygen when the conventional Photo Dynamic Therapy (PDT) with photosensitizers in the excited triplet state cannot work.

Magnetic-plasmonic nanoparticles, combining magnetic and plasmonic components, are promising structures for use in life sciences. Optical properties of core-shell magnetite-gold nanostructures, such as the wavelength of the plasmon resonance, the extinction cross-section, and the ratio of scattering to absorption at the plasmon wavelength are critical parameters in the search for the most suitable particles for envisioned applications. Using Mie theory and the discrete dipole approximation (DDA), optical spectra as a function of composition, size, and shape of core-shell nanospheres and nanorods can be calculated using simulated aqueous media, used throughout the life sciences. Studies indicate that in the advantageous near-infrared region (NIR), although magnetic-plasmonic nanospheres produced by available chemical methods lack the desirable tunability of optical characteristics, magnetic-plasmonic nanorods can achieve the desired optical properties at chemically attainable dimensions. The results can aid in the selection of suitable magnetic-plasmonic structures for applications in life sciences.

Advantages

Plasmonic nanoparticles are being researched as a noninvasive tool for ultrasensitive diagnostic, spectroscopic, and, recently, therapeutic technologies. With particular antibody coatings on nanoparticles, they attach to abnormal cells of interest (cancer

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or otherwise) and once attached, nanoparticles can be activated/ heated with ultraviolet (UV)/visible/infrared (IR), radiofrequency (RF) or x-ray pulses, damaging the surrounding area of the abnormal cell to the point of death.

Many promising therapies are limited by the inefficiencies of drug delivery, therefore, encapsulation of a drug within a nanoparticle can increase efficacy and reduce toxicity by providing greater control over release rate, or by triggering the release at a particular time or location. By controlling the size, shape, surface, charge, and biodegradability of various types of particles, nanomedical formulations have shown efficacy in the clinic with magnetic particle, liposome and nano-polymer based therapies approved for human use.

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