Study of Plasmon Resonance

Lijun Li*, Jingya Liu and Ting Zhu
Henan Normal University, China
Email: *15670569963@163.com

Abstract. Plasma resonance plays an important role in photonic devices, optoelectronic integration, optical sensing, waveguides and biomedicine. So plasmon resonance has become one of the hot spots. In this article, we describe the properties of plasmon resonance, theoretical methods of plasmon resonance in noble metal structures, and some important applications. According to the existing research, the trend of plasmon resonance is analyzed and predicted.

1. Introduction
It is well-known that conduction electrons in metal nanostructures are excited and oscillated. When incident light is irradiated on the metal nanostructures, the collective oscillation of electrons in the metal nanostructures causes resonance of the plasma. Due to the movement of electrons and the accumulation of edge charges, plasma resonance is accompanied by a strong field increase inside and around the metal particles. The resonance phenomenon of plasmon was first discovered experimentally by Wood R W in 1902 [1]. In 1941, Fano et al. explained this resonance phenomenon based on the excitation of surface electromagnetic waves at the air-metal interface [2]. Ritchie found that when high-energy electrons pass through the metal film, the energy loss peak appears not only at the plasmon frequency of the metal film but also at lower frequencies, which is considered to be related to the interface of the metal film. This conclusion was confirmed experimentally by Powell C J and Swan J B in 1959 [3]. In 1960, Stren E A and Farrel R A studied the resonance conditions generated by this mode and proposed the concept of SP for the first time [4], that is, a collective oscillating behavior of the free electrons near the conduction band near the Fermi level on the metal surface driven by the electromagnetic field [5].

Surface plasmon resonance of metal nanostructures has strong local enhancement properties. In this paper, we mainly introduce the characteristics of plasmon resonance of metallic nanostructures, the solution method of plasmon resonance frequency and some application examples based on these characteristics. The resonant frequency depends on the size of the metal structure, materials and the external dielectric environment, which has a wide range of tunable and can selectively scatter and absorb different frequencies of light. It is particularly sensitive to the changes of metal structural parameters and environment, and these advantages prompt the local surface plasmon to be widely studied. With the development of micro-nano processing techniques and characterization methods and the maturing of various chemical and physical synthesis methods of nano-chemistry, nanomaterials with different shapes can be prepared using the corresponding equipment in the laboratory, whose size can reach the order of nanometers. Therefore, the surface plasmon can be widely used in biosensors, optical devices, food safety and so on.

2. Plasmon resonance characteristics
The resonance process of metal nanorods plasmon is shown in figure (a) and (b). The interior of the metal driven by the incident light is disturbed, which breaks the charge balance in some areas and
generates a strong electrostatic restoring force. This can cause the charge of the plasma in the plasma to oscillate. If the oscillation frequency of the electrons is the same as the frequency of the incident light wave, it will produce resonance. The energy of the electromagnetic field is effectively transformed into the kinetic energy of the collective vibration of free electrons on the metal surface in the state of resonance. The mode of resonance can be divided into two kinds, one is the plasmon (as shown in figure a) and the other is the surface plasmon (as shown in Figure b) [6]. For the plasma, it oscillates collectively along the z-axis. As for the surface plasmon, the oscillation is propagated along the surface and exponentially decays in the direction perpendicular to the interface. Surface Plasmon can break through the diffraction limit, and has strong local field enhancement characteristics. Here we briefly describe the characteristics of plasmon resonance.

Figure 1. (a) The displacement of electrons in a rectangular metal bar leads to a Coulombic restoring force, and oscillations at the bulk plasma frequency. (b) Surface Plasmon and Charge Characterization at Metal-Dielectric Interface [6].

Nanoscale particles with different metal components, shapes and sizes have different resonant frequencies of the plasmon. Changing the material, shape, size and around the medium of the particle can dramatically alter the plasmon response of it. Typical examples are gold nanospheres and nanorods. The dipole resonance mode of the gold nanosphere plasmonic redshifts continuously with the increase of its diameter. When the ball is large to a certain extent, the high-polar resonance modes of plasmons can also be observed [7]. As the size of gold nanospheres increases, gold nanospheres exhibit different scattering or absorption properties, so their colloidal solutions show different colors. For gold nanorods, it has two dipole modes of plasmon resonance, which correspond to the resonance of the electrons along the long and short axis of the rod respectively. We call these longitudinal and transverse surface plasmon resonance Mode, in which the plasmon resonance energy of longitudinal surface plasmon is lower [8]. With the increase of the aspect ratio, the dependence of the polarization intensity along the length and the short axis of the nanorods on the wavelength also changes.

Another exciting nature of the plasmon resonance is that it gives a huge scattering or absorption cross section of the noble metal nanoparticles [9]. Scattering and absorbing cross sections quantitatively depict the strength of light-particle interaction. The absorption and scattering spectra of a single metal nanoparticle vary significantly with size and shape [5]. In practice, we can monitor the dielectric environment near the noble metal nanoparticles by measuring the extinction and scattering signals of the local surface plasmon polaritons to create high sensitivity of biosensor.

3. The main theoretical method
The special structure of the nanoparticles makes it have many special properties that different from the bulk material, such as quantum size effect, small size effect and surface effect. The special properties of nano-particles in surface-enhanced Raman spectroscopy, novel sensors, Nano devices and many other fields have a very important role. Fortunately, although plasmonic is a quantum description of
the electron and the electromagnetic field, in general, the plasmons can be accurately described by classical Maxwell's equations when the feature size of structure is not less than 10 nm [10-12]. When the nanoparticle size is less than 10 nm, the quantum confinement effect begins to work [10]. When the nanoparticle spacing is less than 0.5 nm, the effect of quantum tunneling on plasmon can't be ignored [11, 12]. Due to the response of metal nanoparticles to electromagnetic field is described by the local surface plasmon, it is closely related to the small particles' absorption and scattering of electromagnetic fields. The theoretical study of the scattering / absorption of small particles are attributed to the solution of the Maxwell equation set under specific boundary conditions.

In 1908, Mie obtained linear optical properties such as absorption, scattering and extinction of spherical nanoparticles by solving Maxwell's equations and combining the boundary conditions [13]. In 1921, Gans extended the theory of Mie to solve the problem of absorption, scattering and extinction of ellipsoidal particles [14]. But the main disadvantage of the theory of Mie and Gans is that its particle model is confined to spherical and ellipsoid. In the quasi-static approximation, the method of equivalent replacement of the circuit model can also be adopted, which can be solved analytically for some simple models such as nanorods [15-17], L-shaped [18], U-shaped [19], split-ring resonators [17]. However, the previous methods do not solve our model when the metal structure has a more complex shape or is approximately quasi-static failure. We must solve the electromagnetic response of nanostructures by means of numerical methods. The most commonly used numerical methods are finite difference method, discrete dipole approximation method, multiple multipole matrix method and so on.

4. Examples of applications of plasmon resonance in metallic nanostructures

The factors that influence the plasmon resonance frequency are the dielectric constant of the material and the medium, as well as the geometrical size of the nanostructures. Therefore, the plasmon resonance has great and controllable absorption and scattering properties, and it can also focus the energy of the light field in space to a very small scale of nanoscale, which brings a huge enhancement of electromagnetic field. It can be widely used in optoelectronic devices manufacturing, imaging, testing, safety, biomedicine and other fields. Here we briefly list some of the important applications of plasmon resonance.

In the study of improving the integration of optoelectronic devices, plasmon resonance characteristics show an unparalleled advantage. The huge electric field enhancement effect of noble metal nanostructures can give full play to its nonlinear optical properties. For example, the use of a thin layer of metal structure can produce high-frequency optical signals [20]. The mutually coupled noble metal nanostructures can also be used as nano-antennas. It can be used to control the energy transfer in the submicron scale [21], thus it paves the way for the development of integrated optical circuits. The high energy thermal electrons excited when the plasmon decays can tunnel the Schottky junction between the noble metal and the semiconductors. Thus, the noble metal-semiconductor nanostructures can be used to fabricate wide-band, highly integrated photodetectors [22, 23]. It breaks through the limitations of the weak response and high cost of the traditional semiconductor photodetectors in the infrared band.

As we all know, noble metal nanoparticles plasmon resonance occurs in the visible band. The changes of the structure of the noble metal nanoparticles will bring about the change of color. So we can use the color changes to track changes in the environment. For example, a general, dynamic programmable, and cost-efficient time–temperature indicator was constructed the silver plasmons. The reproduction process of bacteria in milk is evaluated according to the process of thermochromic change in temperature control. This method can be used to track and indicate whether the milk is deteriorated during its transport and storage [24].

Another important application is the plasmon resonance sensor. We know that one of the important factors affecting the plasmon resonance frequency is the dielectric constant of the medium. The principle of the plasmon resonance sensor is mainly based on the change of the dielectric constant of the plasmon resonance frequency (or the resonance angle) with the change of the dielectric constant of the metal film adjacent to the metal film generating the plasmon resonance phenomenon. Plasmon resonance biosensors have been widely used in the fields of basic life science, pharmacy, food and
environmental science [25]. In recent years, the development of new technical theories and methodologies has promoted the emerging applications of plasmon resonance biosensors to small molecules, drug screening, 1-bed diagnostics, cell membrane simulation, and proteomics Expansion [26]. As a supplementary instrument used as a traditional clinical monitoring device, the plasmon resonance optical biosensor plays a more and more important role. Van Regenmortel uses biosensors to identify and evaluate potential vaccine components [27]. Ohlson et al. Demonstrated the feasibility of using biosensors to monitor and quantify biologic agents and antibody titers in patient sera [28]. Due to the advantages of real-time monitoring of reaction dynamics, no purification of samples, no labeling of biological samples, high sensitivity and no background interference, plasmon resonance has made great strides in the field of biological sciences. At present, various types of plasmon resonance immunosensors have been developed successfully. A lot of work has been done in protein molecular interaction analysis, DNA hybridization condition, ligand receptor interaction analysis, small molecule drug design and so on. Plasmon resonance technique can also be used to study the interaction between nucleic acids and real-time tracking of the entire nucleic acid reaction process, which is unparalleled by other technologies [29]. After more than 20 years of development, plasmon resonance optical biosensor has become an important research tool in the field of life science.

5. Summary
In summary, we briefly describe the characteristics of plasmonic, theoretical calculations and related applications. With the development of nanofabrication technology, the research on the properties of plasmonic nanostructures is still in progress. Many new problems caused by plasmon resonance have not yet been fully understood. For example, in order to better control the plasmon resonance frequency of metal nanostructures, is there a universally applicable analytic formula. Influence of quantum effect on the properties of plasmon resonance, the new electromagnetic mode produced by plasmons, and so on. Exploring the applications that closely related to plasmon resonance is also constantly moving forward, such as the development of new small and ultra-sensitive bio-detection equipment, information transfer processing on the nano-scale level, the design of inexpensive and highly integrated optoelectronic devices and so on. Therefore, the research of the whole plasmon resonance is still in the developing stage, and there are many studies yet to be completed.

6. References
[1] R. W. Wood, On a remarkable case of uneven distribution of light in a diffraction grating spectrum, Philosophical magazine, 4 (1902), 396-402.
[2] J. Fano, The Theory of anomalous diffraction gratings and of quasi-stationary waves on metallic surfaces (Sommerfeld’s waves), JOSA, 31(1941), 213-222.
[3] R. H. Ritchie Plasma losses by fast electrons in thin films, Phys. Rev., 106 (1957), 874–881.
[4] E. A. Stern, R. A. Ferrell, Surface plasma oscillations of a degenerate electron gas, Phys. Rev., 120 (1960), 130-136.
[5] S. Lal , S. Link, N. J. Halas, Nano-optics from sensing to waveguiding, Nat. Photonics, 1 (2007), 641-648.
[6] M. Staffaroni, J. Conway, S. Vedantam, J. Tang, and E. Yablonovitch, Circuit analysis in metal-optics, Photon. Nanostructures. 10 (1) (2012), 166–176.
[7] Q. F. Ruan et al., Growth of monodisperse gold nanospheres with diameters from 20 nm to 220 nm and their core/satellite nanostructures, Adv. Opt. Mater, 2 (2014), 65-73.
[8] H. j. chen, et al., Gold nanords and their plasmonic properties, Chem. Soc. Rev., 42 (2013), 2679-2724.
[9] Ming T et al., Plasmon-controlled fluorescence: beyond the intensity enhancement, J. Phys. Chem. Lett., 3 (2012), 191-202.
[10] J. A. Scholl, A. L. Koh, J. A. Dionne, Quantum plasmon resonances of individual metallic nanoparticles, Nature. 483 (2012) 421-427.
[11] K. J. Savage et al. Revealing the quantum regime in tunnelling plasmonics, Nature. 491 (2012), 574-577.
[12] R. Esteban, A. G. Borisov, P. Nordtander et al., Bridging quantum and classical plasmonics with a quantum-corrected model, Nat. Commun. 3 (2012), 825.
[13] C. F. Bohren, D. R. Huffman, Absorption and scattering of light by small particles, New York, 1983.
[14] J. Hafer, Goid naopticals are shaped for effect, Laser Focus World. 42 (2006) 99-101.
[15] C. Huang, et al., Study of plasmonic resonance in a gold nanorod with an LC circuit model, Optics Express. 17 (8) (2009), 6407-6413.
[16] Di Zhu, Michel Bosman, and Joel K. W. Yang, A circuit model for plasmonic resonators, Optics Express. 22 (8) (2014), 9809-9819.
[17] H. Ammari, Y. J. Deng, P. Millien, Surface plasmon resonance of nanoparticles and applications in imaging, Springer. 220 (2016), 109-153.
[18] H. Husu et al., Particle plasmon in L-shaped gold nanoparticles, Optics Express. 18 (16) (2010), 16601–16606.
[19] E. Tatartschuk, E. Shamonina, and L. Solymar, Plasmonic excitations in metallic nanoparticles: resonances, dispersion characteristics and near-field patterns, Optics Express. 17(10) (2009), 8447–8460.
[20] S. Kim, et al., High-harmonic generation by resonant plasmon field enhancement, Nature, 453 (2008), 757-760.
[21] A. G. Curto et al., Unidirectional emission of a quantum dot coupled to a nanoantenna, Science, 329 (2010), 930-933.
[22] M. Moskovits, Hot electrons cross boundaries, Science, 332 (2011), 676-677.
[23] M. W. Knight et al., Photodetection with active optical antennas, Science, 332 (2011), 702-704.
[24] C. Zhang, et al., Time–temperature indicator for perishable products based on kinetically programmable Ag overgrowth on Au nanorods, ACS Nano. 7 (2013), 4561-4568.
[25] C. Thirstrup a. W. Zonga. Diffractive optical coupling element for surface plasmon resonance sensors. Sensors and Actuators B 100. (2004), 298—308.
[26] J. S. Yuk, S. H. Jung, J. W. Jung, et al. Analysis of protein interactions on protein arrays by a wavelength interrogation-based surface plasmon resonance biosensor, Proteomics, 4 (2004) 3468–3476.
[27] M. H. V. Regenmortel, et al., Uses of biosensors in the study of viral antigens, A Journal of Molecular and Cellular Immunology, (1997), 67-82.
[28] S. Ohison, M. Strandh, H. Nilshans, Detection and characterization of weak affinity antibody antigen recognition with biomolecular interaction analysis, Molecular Recognition, 10 (1997), 135-138.
[29] Jin W, Lin X, Lv S, et al. A DNA sensor based on surface plasmon resonance for apoptosis associated genes detection. Biosens Bioelectron, 245 (2009), 1266–1269.