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Nanoantennas: from Theoretical Study of Configurations to Potential Applications

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Abstract—In this paper, the present research progress on nanoantennas are described and reviewed. Based on the discussions of different configurations of nanophase material, their potential applications of nanoantenna working in the optical region are presented and compared. From the study of the specified material's properties and the theoretical analysis of proper model, antenna's working fundamentals and the characteristic parameters are investigated from the calculation. The results computed from the electromagnetic simulation and measured form the experiments in practice are proposed to draw a comparison. Finally, we conclude by summarizing some of the applications which have so far the best performance from the use of these novel materials.

1. Introduction

Since the development of material theory and the improvement of fabrication technology, nanophase materials have attracted widely attention in various fields due to their unusual properties. They can be applied in many disciplines such as chemistry, biology, physics and electrics. During recent years, enormous progress has been made in the invention and innovation of nanophase materials used in electromagnetic filed, leading to the increasing interest to study the properties of various nano-structured composites. The research significance of such materials lies in that they has shown the potential of acting as the bridge between the microstructure made of small-sized particles and the macrostructure of continuous media, which causes promising results in electromagnetic field. This topic continues to expand because of its potential properties and applications related with electromagnetic waves, especially the light.

In this work, we focus on several kinds of structures which serve as nanoantenna. We are interested in the difference of performance between nanoantenna and conventional antenna. In addition, the unique properties showed in the nanoantenna for nanometer size are further considered, especially those related to optics. Our research is based on the results both from theoretical analysis and the experimental measurement.

2. Configurations of Nanoantenna

For some nanometer-sized metallic structures, they exhibit amazing properties at optical frequencies. When exposed to light, the coupling of surface plasmons of the nano-materials with light causes the excitation of surface plasmons, i.e. a localized collective oscillation of the free electron gas. As a result, the local field near this metal nano-structure can be dramatically enhanced due to such resonance. The spectral range of the resonant frequencies due to the localized plasmon modes is very large to accommodate the bandwidth of light, which contains different colours. In this way, the nano-structure acts as an optical antenna. Because they can focus light in areas much smaller than the wavelengths, they might be able to detect even a single molecule of a substance, which is not possible with conventional optics.

2.1 Nanoparticles

Because metal nanoparticles are able to produce giant and highly localized electromagnetic fields, considerable interest currently exists for the study of them [1-7]. In this section, we start the discussion from considering the problem of the mismatch between photons and surface plasmons.

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The plasmonic waveguides based on metallic and metallo-dielectric components are being investigated as possible nanophotonic interconnect solutions in future integrated circuits. However, the symmetry of this waveguide has to break in order to achieve an efficient coupling, leading to the interest of exploiting the feasibility of using individual nanoparticles as a means of coupling light into plasmons [8].

Researchers from America recently proposed the opinion of treating a single nanosphere as a nanoantenna in a coupled system [9]. It is shown that this nanosphere realized the antenna's function by coupling incident electromagnetic radiation into low-energy propagating wire plasmons. The research group proved this finding by examining the light-induced coupling between the localized plasmons of a metallic nanosphere and the propagating plasmons of an infinite metallic wire. They found that the plasmon resonances of the coupled system are shifted in frequency relative to the plasmonic structure of the isolated nanoparticles; the magnitude of the shifts depends on the polarization of the incident light and the system geometry. Their conclusion is that, in the limit of a thin wire, a low energy state mainly consisting of delocalized wire plasmons can be induced by the interaction with the nanosphere, i.e. the nanosphere can act as antenna.

In addition to sphere nanoparticles, the nanoscale cylinders are also of great interest. The systems of two and three gold cylinders with distinct resonance frequencies are studied by Spain researchers [10]. The effects of coupling among the plasmon oscillations on the line widths and amplification of the individual particle signals are considered as nanoantenna's behavior. In this study, in terms of the spectral line shapes and spatial intensity near field distribution, the collective behavior of the set of cylinders and spheres has been analyzed. Special attention was paid to the configurations of three interacting cylinders because they showed selective amplification making the set emits like an antenna. That is, using particles that have with different resonant frequencies, the cylinder with highest frequency will amplify the signals of the other two.

Similarly, scientists found out that a device that incorporates nanorods with different resonance frequencies can be used as an antenna or as a molecule specific biological sensor[7]. This is usable in near-field microscopy, which implies an alternative solution to usual tips. In their study, finite-difference time-domain (FDTD) simulation of image distributions and chromatic spectra are carried out and the electromagnetic near-field of a metal nanoring is investigated in the visible range. The capability of nanoring for the use of electromagnetic emission/detection under illumination conditions is interpreted. Nanoring can be interpreted as a particular selective nano-devices playing the role of nanoantennas.

2.2 Nanowire

Since the development of the fabrication technology of nanophase material, it is possible to grown the carbon nanotubes to length of centimeter. At the same time, because carbon nanotube can be metallic, researchers began to suggest a application of carbon nanotubes as antennas [11-15]. Many research groups have exploited this field. Basically, a carbon nanotube can be ideally treated as a thin wire. The RF circuit models have been proposed both for a single nanotube and two parallel nanotubes using transmission line theory [16]. Either by considering the quantum mechanical conductivity or similarity with dipole antenna, the basic parameters such as current, field, efficiency, and the radiation properties are studied [13, 14].

Moreover, the effect of a group of conducting metal wires or the array of carbon nanotubes are discussed [17, 18]. In the composite materials based on parallel pairs of nanowires, both electrical and magnetic resonances can occur in such material, and under certain conditions, it can have a negative refractive index. These nanoantennas or metal composites have the property of being left handed materials as they reverse the properties of electromagnetic waves including the light. They have different surface plasmon polarization modes and thus have different resonant frequencies. The modes are in resonance with the incident radiation, which is light. Thus nanowire composite can act as a negative lens [17].

Reseachers found that the unique resonant characteristics of metallic nanoantennas could be precisely controlled by their geometry and material properties. The polariton resonance frequency in such devices can be tuned to any given range from the optical to the mid-infrared. Applications of plasmonic nanowire composites include narrowand broadband nano-resonators[19], photonics, and left-handed media.

2.3 Bowtie Nanoantenna

Bowtie antennas consist of two metallic triangles facing tip-to-tip that are separated by a small gap. Since the field enhancement is > 10^3 confined to a region near the gap, it may be interpreted as a dramatic improvement in the mismatch between conventional optical excitations and nanoscale structures [20]. In addition, the large enhanced fields in the metal will also lead to similarly enhanced, localized fields on the metallic surface and in between the two bowties. This will yield extremely intense near-field optical light sources with high local contrast that have applications ranging from surface enhanced Raman scattering mechanisms, ultra-sensitive biological detection and nanometer-scale lithography to high-resolution optical microscopy and spectroscopy [21, 22].

Recently Au bowtie antennas have been fabricated for use in the visible by e-beam lithography, and the scattering resonance behavior as a function of gap size for single bowties has been measured and compared with FDTD calculations. In addition, an optical intensity enhancement factor in the gap is measured for light polarized along the line between the two triangles.

Strongly enhanced local fields due to the excitation of surface plasmons in rough films, sharp tips, and nanoparticles give rise to detectable two-photon absorption in Au. Using two-photon-excited photoluminescence (TPPL), scientists directly determine absolute values for optical field enhancements of single Au bowties.

Gold bowtie nanoantenna, with the two triangular pieces of gold about 75 nanometers long, has also been investigated. Instead of amplifying radio waves, this antenna takes energy from an 830-nanometer beam of near-infrared light and squeezes it into a 20-nanometer gap that separates the two gold triangles. The result is a concentrated speck of light that is a thousand times more intense than the incoming near-infrared beam.

3. Simulation and Measurement Approaches

Field enhancement is a study hotspot because this property in optical antennas has the potential applications in the improvement in scanning near-field optical microscopy. This topic has been previously studied by many researchers using numerical simulation. The nanoantenna shapes used in the simulations ranged from single spheres to more complex geometric configurations, in which the same shape is repeated in smaller and smaller sections.

Scientists from Stanford University have used the FDTD method to simulate the current, charge, and field distributions in the antennas. In this way, the relationship between the antenna structure parameters such as shape, length, and sharpness and the intensity of the optical fields produced can be obtained. In addition, optical fields in a bow-tie nano-antenna has been studied using a high-frequency structure simulator (HFSS) [21].Moreover, when investigating the resonant frequency and mode shapes of a single-walled carbon nanotube, the finite element method (FEM) simulations are used [23].

However, some of the ideal conditions cannot be met in practical due to the limitation of fabrication technology. Several experiments are carried out at mid-infrared wavelengths to test the electromagnetic field enhancement in optical antenna arrays [5, 24]. When taking experiments, far-field extinction spectroscopy of the antenna arrays are taken advantaged of to investigate the influence of the antenna's length and material on its resonant wavelength.

4. Applications and Prospects

Typical applications of nanoantennas made of metal nanoparticles include the microscopy, the spectroscopy, and the optoelectronic devices [25-27].

Firstly, in scanning near-field optical microscopy, the localized field enhancement near a metal nanoparticle assembled on a nearfield probe would allow nanoscale features in biological and solid state systems to be selectively illuminated, enabling spatial resolution better than the diffraction limit [2, 3, 28].

In spectroscopy, metal nanoparticle arrays play a role in surface enhanced Raman scattering, and the problem of focusing light beyond the diffraction limit is overcome [1]. Nanoantenna is used by biochemists to dramatically enhance sensitivity in detecting the presence of a molecule on a surface. Engineers from Purdue University have demonstrated through mathematical simulations that nanometer-scale antennas with certain geometric shapes can make possible new sensors capable of detecting a single molecule of a chemical or biological agent[29]. Such an innovation could result in detectors much more sensitive than current technology.

In optoelectronics, ordered arrays of closely spaced metal nanoparticles enable the guiding of electromagnetic energy in subwavelength-sized devices.

In addition, nanoantenna can be used in the field of optical imaging. Although several clever techniques such as darkfield, phase contrast, and interference contrast are provided, all these methods are using the imaging mechanism that the object can only be "seen" when photons originating from it reach the detector. The shortcut of this is that these methods depend sensitively on the intensity, phase, and polarization of light. Researches have shown that we are possible to manage this without receiving illuminated light by monitoring the intrinsic spectral properties of a nanoscopic antenna scanned close to the sample[26, 30]. The spectral modifications of a nanoantenna could serve as the signal to probe the near-field optical contrast of the sample.

Moreover, as what the researchers expected, another application of the nanoantennas is to create more compact, faster circuits and computers that use packets of light, i.e. photons(which travel much faster than electrons),instead of electrons for carrying signals. Such photonic circuits could be used for a new type of sensitive sensors which detect tiny traces of chemicals and biological materials, making them useful for applications including analyzing a patient's DNA for medical diagnostics, monitoring air quality for pollution control and detecting dangerous substances for homeland security. In addition, with new types of materials, it may be possible to accomplish better performance than all existing materials, in terms of making images and manipulating light. If Light can be manipulate and guide by employing the plasmonic nanomaterials, all the basic fundamental properties of electronic circuits can be basically simulate by the replace of photons.

5. Conclusions

In conclusion, we make a brief overview on the recent progress in nanoantenna. We examine the electromagnetics and physics of nanoantenna, including the aspects of possible configurations and models, working mechanism, and antenna applications to further understand the properties of nanoantenna. The nanophase material designs, simulation with software and test approaches using experiments are also reviewed. For the theoretical analysis of nanoantennas, the FDTD method is an effective approach to the calculations of the current, charge, antenna shape, length, and sharpness and field distributions in the antennas. The research of nanoantennas is found to be of potential optical applications to microscopy imaging, the optoelectronic devices like sensors or detectors, and a way to study photons circuit.

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