論 文 の 内 容 の 要 旨

論文題目　Interaction of angular momentum between light and plasmonic nanostructure
（光とプラズモニックナノ構造間の角運動量の相互作用）

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Angular momentum, as a basic property to describe the rotation of light, can be separated into spin angular momentum and orbital angular momentum. The interaction of angular momentum between light and matter gives rise to a wide variety of physical interactions and has been extensively studied since it can induce many striking optical phenomena. Especially, in recent years, the rapid development of plasmonics and nano-optics have extremely facilitated the study of the interaction of angular momentum between light and matter with numerous applications. However, in such a large research field, there are still many issues that have not been well studied. In this research, we carry out three topics in the interaction of angular momentum between light and matter to improve the insights into the physics of light-matter interaction and to expand the applications.

1. Quantification of the optical spin-orbit transformation in light-matter interaction

When light interacts with matter, there is a transformation between the spin and orbital parts of the angular momentum carried by the light. This spin-orbit interaction of light is highly related to the spatial and polarization degrees of freedom of light, which plays a crucial role in the manipulation of light. Most of the spin-orbit interaction appears at subwavelength scales. The description of the spatial and polarization properties of light at subwavelength scales provides a new viewpoint for the physical insight at subwavelength scales. Moreover, the interaction between spin and orbital degrees of freedom makes it possible for optical nano-devices to have novel functionalities. In the past three decades, with the rapid development of nano-optics, photonics, and plasmonics, the spin-orbit interaction of light has been attracting rapidly growing interest due to its promising potential in many practical applications [1-3].

However, thus far, we have been unable to separately analyze the spin and orbital angular momenta in light-matter interaction because it is very difficult to evaluate the angular momentum, especially the orbital angular momentum, in the scattering field generated by the light-matter interaction. Therefore, it will greatly benefit the design and analysis of a spin-orbit interaction system if we can realize the quantification of the spin-orbit transformation.

In this topic, we propose a method for analyzing the angular momentum in the light-matter interaction by separately characterizing the transfer of spin angular momentum from that of orbital angular momentum. In analogy to the continuity equation for linear momentum, we obtain the continuity equation for spin angular momentum from the flux of optical chirality density. The derived equation can calculate the spin-transfer torque separately from the orbit-transfer torque, which provides a quantitative analysis method for the optical spin-orbit transformation in light-matter interaction. What is more, this is a general method that can be applied to any size, shape, and constituent of matter in the presence of arbitrarily structured optical fields. The separation of spin-transfer torque and orbit-transfer torque may play a significant role in analyzing and designing a spin-orbit interaction system, which can be applied to many fundamental processes such as optical manipulation of nanoparticles and molecules, subwavelength optical probing, and generation of vortex beams. Our approach to separating the transfers of spin and orbital angular momenta will provide a better understanding of the fundamentals of the physics of the interaction between light and matter.

2. Optical torque between twisted metal nanorods induced by plasmon coupling interaction

The angular momentum transfer between light and matter can produce an optical torque on the matter. It provides a rotational mechanical degree of freedom to manipulate objects. Particularly, due to the strong interaction between light and plasmonic nanostructures induced by the excitation of localized surface plasmon resonances, optically driven plasmonic nanostructures establish an extremely interesting platform for nanomechanical engineering and sensing applications. Over many decades, optical torque has been attracting widespread attention owing to its crucial role in optical manipulations, with a variety of applications in physics, chemistry, and biology [4, 5].

Many remarkable achievements have been made in the study of optical torque, however, these studies mainly focus on an individual nanoparticle. Few works are trying to study the optical torque in a multi-particle system. When two nanoparticles are close to each other, plasmon coupling occurs due to the strong interaction between them, resulting in an appearance of two plasmon coupling modes different from individual constituents. In some previous studies, it has been reported that the plasmon coupling can produce a large interaction optical force on each nanoparticle [6, 7], which plays a significant role in the optical arrangement. Intuitively, interaction optical torque is also very important in the optical arrangement because it provides another mechanical degree of freedom for the manipulation of particles.

In this topic, therefore, we study the interaction optical torque induced by plasmon coupling in a dimer of twisted metal nanorods. We start with the plasmon coupling in the dimer which can be explained by the theory of plasmon hybridization. We then discuss the optical torque on the twisted nanorods. We study the direct relation between the optical torque and plasmon coupling. The results indicate that the behaviors of the interaction optical torque at hybridized modes are different from that of an isolated nanorod, which depends not only on the gap size but also on the twisted angle between the nanorods. The interaction optical torque implements the rotations to mutually perpendicular and parallel arrangements of nanorods with the excitations of different hybridized modes. Thus, the interaction optical torque induced by the plasmon coupling would realize the dynamical contactless control of the plasmonic characteristics and functions, e.g., the field enhancement, plasmon resonance, and chirality, through the nanoparticle configurations with the plasmon coupling. Our findings will open a new route to all-optical active plasmonic and metamaterial devices, such as high-precision plasmonic nanodevices and nanomachines.

3. Enhancement of *g* factor of twisted metal nanorods by plasmon coupling

Chiral objects are those objects which cannot be superimposed with their mirror image. Chirality is very common in nature that reflects a fundamental property of materials. Chiral material can manifest a chiroptical response via the different absorption of left- and right-handed circularly polarized light, which can be quantified by the dissymmetry factor (*g* factor). This chiroptical phenomenon is of great significance in fundamental research and successfully applied in many different fields. However, this chiroptical response is inherently weak for most natural chiral materials due to the small size of molecules, which limits its further studies and applications.

Recently, chiral plasmonic nanostructures have attracted widely scientific interest because they can strongly interact with circularly polarized light as well as with chiral molecules and can be designed to mimic the properties of chiral molecules. With the development of nanotechnology, chiral plasmonic structures with large *g* factor have shown promising potential for detecting and sensing applications, negative refraction materials, and optical elements with strong chiroptical effects [8-10]. Therefore, the study of the enhancement of *g* factor will be of great significance to improve the insights into controllable chirality of nanostructure and to expand its application. However, in the previous studies, almost all the studies of the *g* factor enhancement are limited to the geometry design of the structure.

In this topic, we investigate the *g* factor at hybridized modes induced by the plasmon coupling in the dimer of twisted nanorods, which provides a new perspective for the study of *g* factor enhancement. We experimentally demonstrate that the plasmon coupling between the twisted nanorods can enhance the *g* factor of the structure, depending not only on the gap size but also on the twisted angle. The *g* factor at the hybridized bonding mode exhibits a very high value comparing with that in previous studies. We believe that the study of *g* factor enhancement with the plasmon coupling provides an efficient route for designing chiral metamaterial with a highly enhanced chiroptical response and is generally applicable to other chiral plasmonic metamaterials for practical applications.

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