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Review article

Coupling of a single active nanoparticle to a polymer-based photonic structure

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ABSTRACT

The engineered coupling between a guest moiety (molecule, nanoparticle) and the host photonic nanostructure may provide a great enhancement of the guest optical response, leading to many attractive applications. In this article, we describe briefly the basic concept and some recent progress considering the coupling of a single nanoparticle into a photonic structure. Different kinds of nanoparticles of great interest including quantum dots and nitrogen-vacancy centers in nanodiamond for single photon source, nonlinear nanoparticles for efficient nonlinear effect and sensors, magnetic nanoparticles for Kerr magneto-optical effect, and plasmonic nanoparticles for ultrafast optical switching and sensors, are briefly reviewed. We focus further on the coupling of plasmonic gold nanoparticles and polymeric photonic structures by optimizing theoretically the photonic structures and developing efficient way to realize desired hybrid structures. The simple and low-cost fabrication technique, the optical enhancement of the fluorescent nanoparticles induced by the photonic structure, as well as the limitations, challenges and appealing prospects are discussed in details.

1. Introduction

Nanotechnology has caught wide attention and imagination in such a short period of time. Many ideas from science fiction became a reality following the invention of advanced instrumentation such as the super-resolution optical microscope (OM), scanning electronic microscope (SEM), atomic force microscope (AFM), scanning tunneling microscope (STM), transmission electron microscope (TEM), etc., all of which made it possible to see and manipulate nanostructures and nanoparticles.

Nanotechnology deals with materials and systems at or around the nanometer scale. It has been found that many materials and structures with a dimension below 100 nm have properties and characteristics dramatically different from their bulk forms [1]. Therefore, the 100 nm dimensional scale has set the boundary between nanotechnology and all other microscale, mesoscale, and conventional macroscale technologies. There are many subject areas under the banner of nanotechnology, such as nanoelectronics, nanomaterials, nanomechanics, nanomagnetics, nanophotonics, nanobiology, nanomedicine, etc. [2].

The key to nanotechnology is the imaging and fabrication of various nanostructures. Among commercially available microscopy techniques, the conventional OM is most widely used in optical experiments due to its simplicity and low-cost. Nowadays, the OM is a necessary tool of any multidisciplinary laboratory. Moreover, owing to the use of a high numerical aperture objective, the optical resolution of OMs (down to sub-wavelength scale) will allow many interesting physical phenomena to be explored. An OM can optically address a small object in two ways: it can image the nano-

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object and/or be used to fabricate the nano-object. For example, an optical nanofocusing spot has the potential to increase the capacity of a memory disk from several gigabits to even a terabit by densely packing bits and reading them at nanoscale. Although there is a long way for this optical nanotechnology to become realized, its potential motivates its continued research in the nanoscience and nanotechnology community.

Together with the ongoing development of more efficient optical nanotechnology, a great deal of interest has been devoted to working with suitable and inexpensive materials to form desired nanostructures. In fact, the major challenge in nanostructures study is the fabrication of these structures with sufficient precision and processes that can be robustly mass–produced [3]. Organic or polymer materials have recently appeared as the material of choice for the fabrication of photonic devices, such as light emitting diodes, integrated lasers, photovoltaic cells, and photodetectors, etc. [4]. Organic molecular systems offer unique opportunities in nanophotonics since both top-down and bottom-up strategies can be pursued towards the nanoscale. Indeed, nanotechnology approach permits down-scaling the patterning of polymer materials in order to build either single nano-objects (*e.g.*, nanocavity, single quantum device, nanolaser, etc.) or nanostructured materials (*e.g.*, photonic bandgap materials, distributed feedback lasers, resonant waveguides gratings, etc.) [5].

In particular, polymer materials could be functionalized with active materials (nonlinear optical, fluorescent, etc.) of different forms (organic, inorganic, metallic, etc.). The ensemble can be optically structured to obtain a polymer-based photonic nanostructure (the host) containing active materials (the guest). This host/guest coupling can have the mutual effects, depending on the specific application. The photonic structure can, for example, enhance the nonlinear optical property of the guest owing to the field confinement effect and the anormal dispersion effect [6,7] or by modifying the fluorescent property through the Purcell effect [8,9]. In other cases, the guest can also modify the optical properties of host photonic systems. For instance the photoinduced effect of doped nonlinear polymer materials can help to modify the refractive index contrast of the whole structure, thus tuning the so-called photonic bandgap of the photonic structure [10,11].

Besides, nano-object or nanoparticle (NP) research is currently of great scientific interest due to a wide range of potential applications in biomedical, optical, and electronic fields. NPs are effectively a bridge between bulk materials and atomic or molecular structures. They possess size-dependent properties such as quantum confinement in semiconductor particles, surface plasmon resonance in metal particles and superparamagnetism in magnetic materials. These featured properties make NPs the key factor in many recent research studies. Specifically, semiconductor quantum dots [12] or nitrogen-vacancy (NV) centers in diamond nanocrystals [13,14] can serve as single photon emitters in quantum optics or quantum information applications [15]. Additionally, magnetic NPs can be used for data storage [16,17] and biomarkers [18], while metallic NPs can be used as thermal nanosources [19,20] and to strongly enhance local electromagnetic fields [21]. Nonlinear NPs can be also used as biomarkers [22] or as sensitive sensor systems [23].

Recently, the concept of a photonic structure (PS) containing fluorescent molecules or active nano-objects has drawn great attention due to their wide range of applications. Fig. 1 illustrates the general idea of coupling a single NP to a PS. The different classes of single NPs (quantum emitter; metallic, magnetic, and nonlinear NPs) can also be envisioned to be coupled with desired PSs for specific applications. For instance, self-assembled quantum dots embedded in a distributed Bragg reflector cavity structure [12,24], a single semiconductor NP in a periodic one-dimensional plasmonic structure [25], or a single NV color center in diamond incorporated with a resonator [26,27] have been proposed for optimizing a single photon source. For the control of light–matter interaction at the nanoscale, a gold NP coupled with a cavity system [28] was also demonstrated. Although NP/PS coupling has been intensively investigated both theoretically and experimentally, the fabrication of such functionalized nano- or micro-structures still remains a great challenge since most NP/PS coupled structures require complicated and expensive techniques.

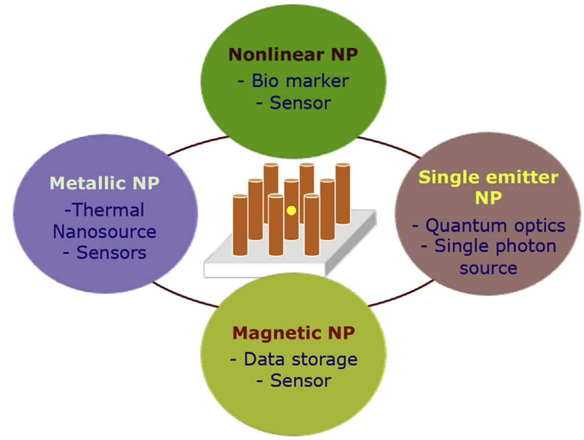

Fig. 1. Illustration of coupling of a single active nanoparticle into a two-dimensional photonic structure. Different kinds of single nanoparticles (quantum emitter; metallic, magnetic, and nonlinear nanoparticles) could be coupled for different applications.

In this article, we begin by introducing several systems where various kinds of NPs are coupled into PSs and describe how the properties of those NPs are optimized. We then discuss further about the plasmonic/photonic coupling and present some theoretical calculations related to this subject. Finally, we describe a simple and low-cost fabrication technique to precisely couple a single gold NP into a polymer-based PS with detailed discussions.

2. Review of coupling of a single active nanoparticle to a photonic structure

2.1. Enhanced single photon source

Over the last few decades, the explosive development of quantum information science has prompted profound research into single photon source [29,30]. Indeed, this quantum light source can be used as an ideal element for fundamental research, for example, for demonstration of the laws of quantum physics [31]. A single photon source can also serve for different practical applications, such as quantum computing or quantum communication. Actually, single photons can act as quantum bits (qubits) for storing information in their quantum state [32] since the travel speed of photons results in the weak interaction with the environment over long distances, hence reducing noise and loss. Researchers thus dream to be able to realize in the near future a so-called quantum computer [33,34], which helps perform tasks more efficiently than classical computation. In quantum cryptography or quantum key distribution, the use of single photon source allows the distribution of a secure key [35,36], avoiding the leakage of information to an eavesdropper, which occurs with a classical communication method.

For all these applications, the first step is to generate an efficient and integrable single-photon source, which should meet some requirements such as brightness, controllability, narrow spectrum,