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Tunable multiple plasmon resonances and local field enhancement of a structure comprising a nanoring and a built-in nanocross

Jianxia Qi [a,b], Runcai Miao [a,*], Caixia Li [a], Mingdi Zhang [a], Yanni Wu [a], Chi Wang [a], Jun Dong [c,*]

[a] School of Physics and Information Technology, Shaanxi Normal University, Xi'an, 710000, China
[b] School of Science, Xi'an University of Posts and Telecommunications, Xi'an 710121, China
[c] School of Electronic Engineering, Xi'an University of Posts and Telecommunications, Xi'an 710121, China

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ABSTRACT

This paper proposes a plasmonic nanostructure comprising a silver nanoring and a built-in nanocross (NRC). The plasmon resonance coupling of the NRC was investigated by numerical simulation. The NRC produced multiple resonances and strong electric field enhancement. The resonance position was tuned by changing the parameters of the nanostructure. The corresponding electric field enhancement was observed in different areas of the NRC nanostructure. The adjustable plasmon resonance and the enhanced electric field exhibit potential for subwavelength lithography, surface-enhanced spectroscopy, and biochemical sensing.

1. Introduction

When incident light is present on the metal nanoparticle surface, conduction electrons in the nanoparticles are excited, and localized surface plasmon resonance (LSPR) is produced [1,2]. The strong plasmon resonance peak appears in the extinction spectra due to the LSPR effect, and the strong electromagnetic (EM) fields surrounding the nanoparticles appear and are localized to the nanoscale region, known as "hot spots" [3,4]. This field is highly localized to the nanoparticle and decays rapidly from the nanoparticle interface into the dielectric background. The highly localized EM intensity enhancement is a very important aspect of LSPRs and has been applied successfully to surface-enhanced spectroscopy analyses, such as surface-enhanced Raman scattering (SERS) and surface-enhanced fluorescence(SEF) [5–7].

The position of resonance peaks depends on nanoparticle shape and size and gap between the particles and the dielectric environment [8,9]. Various nanostructures have been designed to tune the plasmon resonance, from simple to complex structures [10–13], from monomers to polymers [14,15], and from two-dimensional to three-dimensional topologies [16,17]. With the rapid development of modern technologies, such as electron beam lithography, nanosphere lithography, electrochemical method, and on-wire lithography [18–21], different nanostructures with novel optical properties have been developed.

Among various shaped nanostructures, ring-shaped metal nanostructures exhibit interesting properties [21–24], and can produce strong EM coupling between the inner and outer ring walls when thickness d is smaller than ring radius r. Hence, multiple parameters of a single nanoring can be tuned; these parameters include inner and outer radii and height of the structure. The tunability of nanorings has been exploited in the design of plasmonic waveguides in the optical telecommunication band [25]. Furthermore, Prof. G.C. Schatz group have systemically investigated the LSPR properties with metallic nanorings both from experimental and computational aspect. Solution-dispersible metal nanorings with varies size were obtained with chemical method, and it is found that simulation results coincide with the experimental results well [26].

A nanocross, which comprises two rods perpendicular to each other, sustains broad dipole and sharp high-order localized surface plasmon resonances [27–30], The spectral position can be easily controlled by varying the arm length, arm angle, and light polarization. Theoretically, any branch of a nanocross can be excited, and the plasmon resonance coupling of each branch leads to electric field enhancement [31,32].

In this paper, we propose a new structure that combines a ring and a cross. The plasmon resonance of this structure can be tuned by all the parameters of the ring and the cross. As such, several parameters can be used to modulate the LSPR of the structure. Moreover, high order plasmon resonance and electric field enhancement can be generated in the NRC structure. In the current work, we present a theoretical investigation of the optical properties of NRC and discuss three cases. The first case is tuning the crossing angle when the intersection point of the cross overlaps with the ring center. The second case is moving the intersection point of the cross to the left. The third case is modulating the

* Corresponding authors.
E-mail addresses: rcmiao@snnu.edu.cn (R. Miao), dongjun@xupt.edu.cn (J. Dong).

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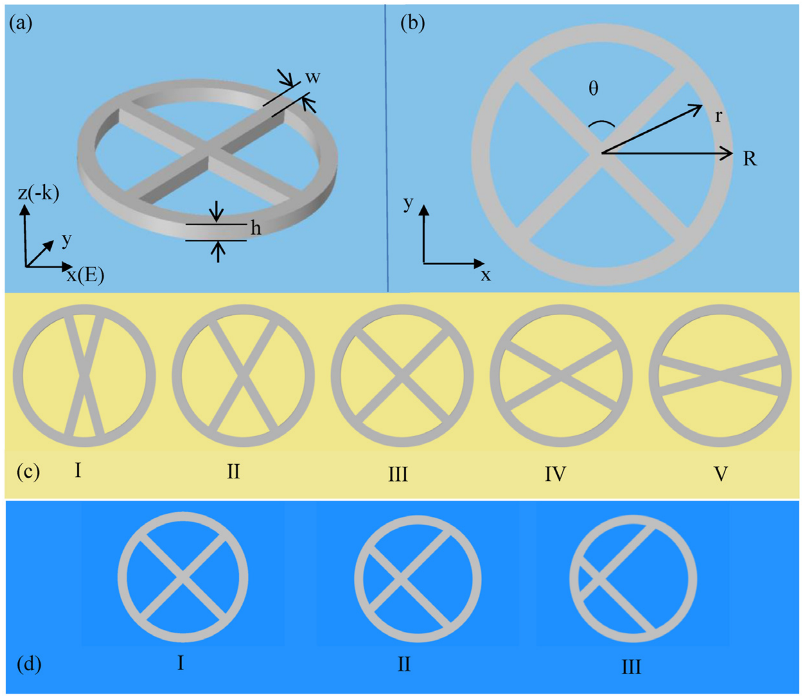

Fig. 1. Schematic of the model: (a) 3-D schematic of the structure. The negative direction of incidence $-k$ and the polarization direction E are denoted on the left bottom. (b) 2-D schematic of the structure in the x–y plane. (c) 2-D schematic of the structure evolution with the crossing angle changing from 30° to 150°. (d) 2-D schematic of the structure evolution with the intersection point of cross moving left.

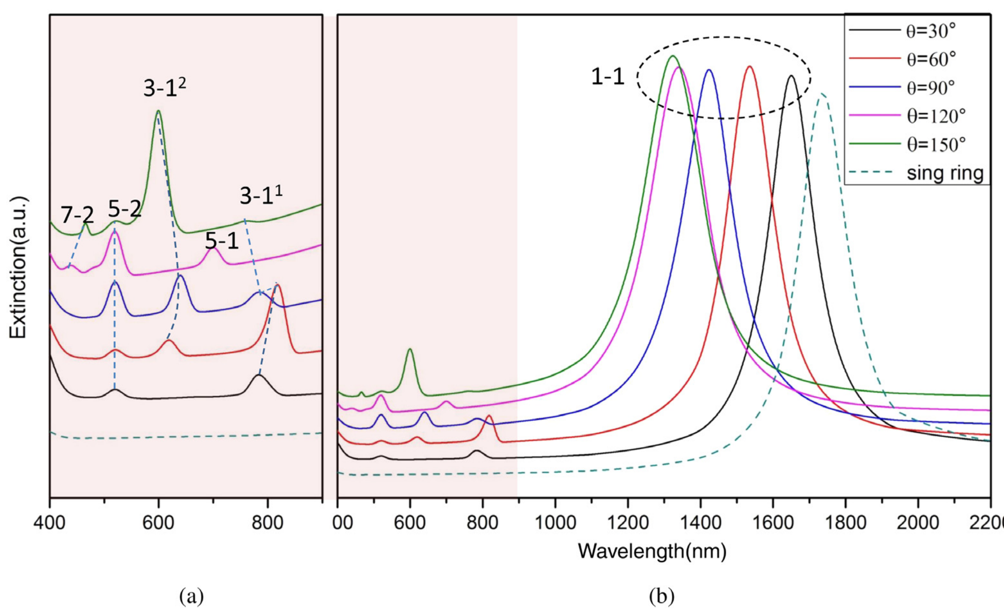

Fig. 2. Extinction spectra of single ring(dashed line) and the NRC with different crossing angle (solid lines). The width of cross is fixed at 20 nm and the outer and inner radius of the nanoring are fixed at 150 nm and 130 nm, respectively. Fig. 2(a) is the extended diagram of shadow zone of Fig. 2(b). The mode of the resonance peak is marked on the graph.

size of the geometric structure. Different high order plasmon resonances are produced by modulating the parameters of the NRC, and the regions of hot spots vary in different modes.

2. Structure and method

Fig. 1 illustrates the geometric structure that is composed of a nanoring and a built-in nanocross. The structure appears similar to the signal of the tensor product. Fig. 1(a) shows the 3D schematic of the structure, and Fig. 1(b) shows the 2D schematic of the structure in the x–y plane. Fig. 1(c) I–V shows the 2D schematic of the structure evolution as the crossing angle increases from 30° to 150°. Fig. 1(d) I–III presents the intersection point of the cross that moves to the left when the crossing angle is fixed at 90°. The distances from the intersection point to the ring center shown in Fig. 1(d) I–III are 0, 40, and 80 nm, respectively. The relative parameters of the NRC are as follows: outer