Unidirectional lasing with symmetry broken core-shell nanoparticle

Urcan Guler, Xiangeng Meng, Vladimir M. Shalaev*, and Alexander V. Kildishev
School of Electrical & Computer Engineering and Birck Nanotechnology Center, Purdue University, West Lafayette, IN 47907, USA
**shalaev@purdue.edu*

Abstract: We propose a plasmonic laser with uni-directional power outflow based on a symmetry broken core-shell nanoparticle. A detailed study of the emission mechanism of the sub-wavelength, directional light source is provided.
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Introduction

Subwavelength lasers based on gain assisted plasmonic nanoparticles (spasers) have recently attracted attention due to a unique emission mechanism allowing coherent local fields [1, 2]. Due to the unconventional mechanism of nanoparticle based plasmonic lasers, light emission in a confined direction is not achievable with the approaches reported so far. Recently, we reported initial results on a nanoparticle spaser with geometrical asymmetry that leads to directional emission independent of the incidence angle and polarization of pump light [3].

Partially covered core-shell structures supporting dipolar modes causing scattering with modified electric field has been studied both numerically and experimentally [4]. Confinement of the mode due to limited coverage of the shell is found to be responsible for the modified scattering profile. However, higher order modes were not observed due to the small sizes of those particles. The quadrupolar mode that occurs when the size of the particle is large enough has unique scattering properties, leading to directional power flow from the core-shell structure. In this work, we present a detailed analysis of partially covered core-shell structures that provide unidirectional emission when properly designed. Materials chosen in this study are Ag as the shell and SiO_2 as the core of the particle. The SiO_2 core in design is a porous structure, allowing diffusion of laser dye molecules into the particle.

Figure 1(a) gives the illustration of a symmetry broken core-shell particle with one-half coverage under illumination at 90-deg angle of incidence. It has been shown that new plasmonic modes emerge when the shell coverage deviates from a nanoshell and fundamental dipolar and quadrupolar modes evolve resulting in unique scattering profiles [3]. Figure 1 (b) shows the absorption efficiencies (Q_{abs}) for core-shell particles with half (semi-shell) and full (nano-shell) coverages. One can clearly see the deformed dipolar modes occurring at wavelengths above 600 nm for the semi-shell case. Similarly, quadrupolar mode is modified and has high quality factor for both coverages.

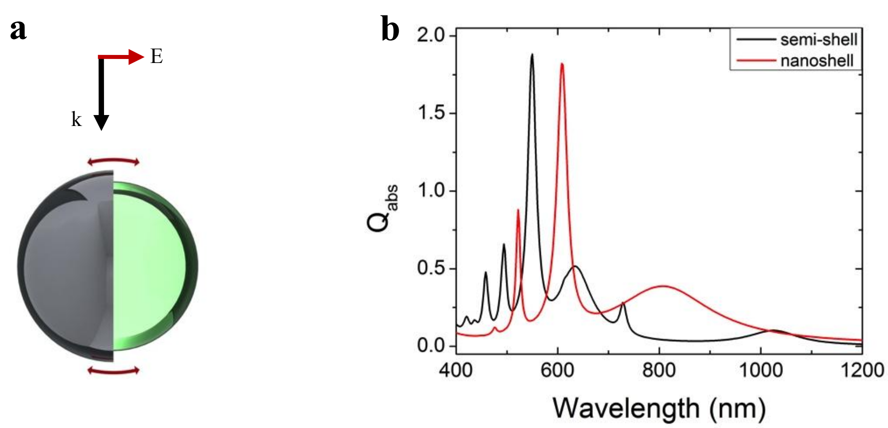

Fig. 1. (a) Illustration of symmetry broken core-shell particle under illumination with 90° angle of incidence. Rounded arrows show the direction of the change in the shell coverage ratio that changes the lasing condition dramatically. (b) Absorption efficiencies of a nanoshell and semi-shell.

Particularly interesting properties arise when the quadrupolar mode of the semi-shell particle is excited. In addition to the high quality factor of the resonance peak, the profile of the power flow due to the scattered field shows unidirectional behavior independent of the angle of incidence and polarization of illuminating light. Figure 2

(a) shows the angular distribution of the radial component of power flow from a semi-shell particle under 90° illumination with a wavelength of 550nm. Total power outflow from the particle has no distinct directionality. On the other hand, as shown in the inset, the scattered component of the power is mainly concentrated around a specific angle. Introducing gain into the porous SiO_2 core amplifies the scattered power from the particle and under lasing conditions directional emission can be obtained. The directionality of the power flow is independent of incidence angle and polarization of pump light.

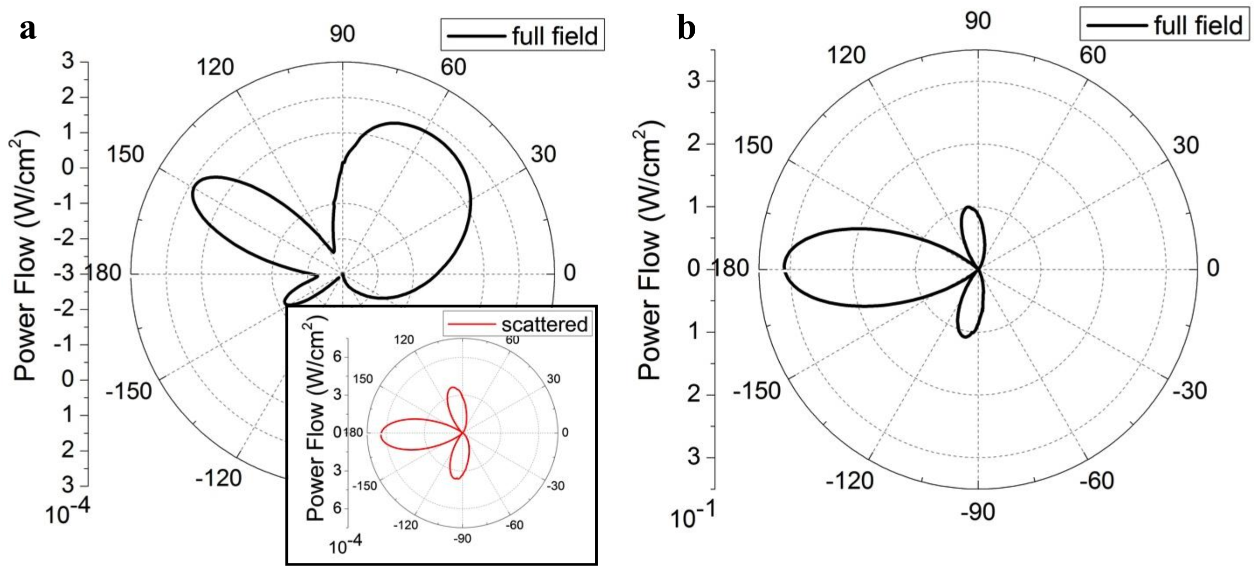

Fig. 2. (a) Total power flow in the radial direction when a semi-shell with no gain is illuminated. Inset shows the power flow due to the scattered component which is enhanced when gain is introduced to the system. (b) Total power flow from the same particle when gain material is embedded in the porous SiO_2 core. Enhanced scattered component clearly dominates the total power flow and provides directional emission from the symmetry broken spaser.

Because the resonances of the structure arise from the plasmonic oscillations of the metallic shell, coverage of the shell plays crucial role in determining the lasing properties. Simulations show that increased shell coverage relaxes the poles of the quadrupole and changes the quality factor of the plasmonic peak. This effect directly leads to a change in lasing wavelength and efficiency of the structure. On the other hand, reducing the coverage results in a smaller metal content and reduces the extinction efficiency. Consequently, optimum results can be obtained from structures with coverage around 50%.

In summary, we propose a symmetry broken core-shell structure as a sub-wavelength spaser with directional power output independent of the angle of incidence and polarization of pump light.

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