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Low threshold nanorod-based plasmonic nanolasers with optimized cavity length

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HIGHLIGHTS

- Introducing two spasers based on one-dimensional arrays formed by three nanorods.
- Reducing the lasing threshold and the normalized mode area by utilizing an extra gain medium.
- Reducing the large wave vector of the lasing mode by using an extra metallic core.
- Obtaining more precise lasing threshold by accurate selection of the cavity length.

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ABSTRACT

In this article two optically pumped nanorod-based plasmonic nanolasers which composed of two coupled metal-insulator-semiconductor (MIS) hybrid plasmonic waveguides are investigated. In the first structure, a common metallic nanorod is utilized to construct a semiconductor-insulator-metal-insulator-semiconductor (SIMIS) nanostructure while in the second one, the semiconductor part is shared and a metal-insulator-semiconductor-insulator-metal (MISIM) based plasmonic nanolaser is formed. Simulation results based on the finite element method (FEM) show that the SIMIS structure with nanorods' radii of 40 nm and insulator layer thickness of more than 12.67 nm has lower threshold and simultaneously lower normalized mode area at the lasing wavelength of 490 nm compared to the previously reported MIS nanostructure with the same parameters. The simulation results for the second proposed structure show that the MISIM based spaser has a lower effective mode index and consequently lower wave number at the wavelength of 490 nm, compared to both SIMIS and MIS based nanocavities. This results in less challenge for coupling to on-chip waveguides. The cavity length of the presented nanorod-based spasers has been optimized by considering the lasing mode propagation distance as the nanocavity length which leads to a better light matter interaction enhancement.

1. Introduction

Spaser or surface plasmon amplification by stimulated emission of radiation was suggested by Bergman and Stockman in 2003 [1]. Although spaser originally describes the feedback mechanism based on localized surface plasmons (LSPs), more recently it has also been applied to plasmonic nanolasers based on propagating surface plasmon polaritons (SPPs) [2]. One important advantage of SPP-based nanolasers compared to LSP-based ones, is the capability of using them as inline cavity or waveguide integrated plasmonic nanolasers due to better light coupling to on-chip waveguides. It is shown that utilization of a waveguide-integrated nanoscale plasmon source can realize high coupling efficiency of $\sim 60\%$ and a small footprint of $\sim 0.06\ \mu m^2$ which is suitable for dense integration [3]. The results of the recent researches on waveguide-integrated configuration show experimental evidence of lasing emission and its coupling into the propagating modes of a plasmonic waveguide based on V-groove structure [4]. This makes possible on-chip routing of coherent and subdiffraction confined light at room temperature. The first successful laboratory sample of SPP-based spaser or plasmonic nanolaser was created by Oulton et al. at the lasing wavelength of 490 nm [5]. The structure was based on metal-insulator-semiconductor (MIS) platform in which a semiconductor nanorod is placed on a metal film with an insulator gap. They had also designed a similar structure as a hybrid plasmonic waveguide [6]. The semiconductor nanorod acts as the gain medium and its end facets form a microscale Fabry–Perot (FP) cavity [7]. This nanorod-based MIS platform which supports propagation of the hybrid plasmonic modes, has been widely exploited in many researches during the past decade. In

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2010, Zhu investigated the modal properties of this MIS structure at the same lasing wavelength [8]. Similar structures with different materials [9] and also various nanorod structures such as core–shell [10,11], multi-quantum-well (MQW) [12,13], hexagonal [14–17], and triangular [18] have also been presented. The idea of using more than one nanorod in a MIS structure was proposed by Bian et al. in 2012 [19]. They designed a long range hybrid plasmonic waveguide based on coupled nanowires with simultaneously subwavelength mode confinement ($\sim\lambda^2/460$ to $\lambda^2/35$) and long range propagation length ($\sim$33 to 1260 μm) at the wavelength of 1550 nm. Then, they introduced a low threshold plasmonic nanolaser based on two coupled nanorods by using a CdS nanorod as semiconductor gain material alongside a core-shell structure with Ag as metallic core and MgF_2 as insulator shell [20]. Their idea and results have inspired many subsequent researches in recent years [21–23]. It is specified that the coupling of long range SPP and dielectric nanorod modes can provide a mode confinement level similar to a hybrid plasmonic mode with one order of magnitude longer propagation length [24]. In this work, we propose and analyze two optically pumped nanorod-based spasers at the lasing wavelength of 490 nm with semiconductor-insulator-metal-insulator-semiconductor (SIMIS) and metal-insulator-semiconductor-insulator-metal (MISIM) nanostructures. These structures can support propagation of LRHPP modes at the telecommunication wavelength [19]. Although there is a compromise between the normalized mode area and the lasing threshold, by utilizing the SIMIS structure, we can achieve a lower normalized mode area and at the same time, a lower threshold compared to MIS nanostructure. On the other hand, the MISIM based nanolaser can realize lower propagation loss and lower effective index compared to both SIMIS and MIS based nanolasers. In the similar simulations on nanorod based plasmonic nanolasers, a constant value is commonly used for the nanocavity length in the plasmonic nanolaser structure [8,13,20,21]. According to the relationship between the propagation length of the hybrid plasmonic mode and the geometric parameters values, it's not absolutely true to assume a constant value for the cavity length. So, we modify this assumption and accordingly the calculation of the lasing threshold in the presented structures.

The remainder of this paper is organized as follows. In Sections 2 and 3, the SIMIS- and MISIM- based nanolasers are introduced and analyzed, respectively. In Section 4, the necessity of optimization of the nanocavity length is discussed and the lasing threshold of two structures are simulated again. Finally, the paper is concluded in Section 5.

2. The SIMIS-based plasmonic nanolaser

The three dimensional schematic of the first proposed spaser and its cross-sectional view are shown in Fig. 1 (a) and (b), respectively. As shown in these figures, a core-shell structure with Ag as metallic core and MgF_2 as insulator shell is placed between two CdS nanorods as semiconductor gain materials on MgF_2 substrate. So, this plasmonic nanolaser has a waveguide structure as semiconductor-insulator-metal-insulator-semiconductor (SIMIS). Such structure can be fabricated by using self-assembly techniques [20].

The distance between two semiconductor nanorods and the metal core is always the same and defined as h. r_1 and r_2 are the radii of Ag and CdS nanorods, respectively. It is assumed that $r_2 = r_1 + h$. The lengths of three nanorods are equal and defined as L. Since Ag is used as metal, MgF_2 as insulator, and CdS as semiconductor gain material, the lasing wavelength of the plasmonic nanolaser is 490 nm [5]. At this wavelength, the refractive indices of Ag, MgF_2 and CdS are 0.05 + 3.039i, 1.4 and 2.4, respectively.

As Oulton et al. mentioned in [5], the mode area and the emission rates depend on the nanorod diameter. Due to the dependence of exciton dynamics to the size of nanorods [25], it is more precise to use a limited range for the nanorods radii in the simulations. So, according to the assumptions and results of references [5,20], we have selected three different values of 40, 50 and 60 nm for the nanorods radii.

In the following, we first obtain the electric field distribution at the device cross section and then calculate the propagation characteristics.

According to the fact that our SIMIS structure consists of two coupled MIS hybrid plasmonic waveguides sharing a common metallic nanorod, existence of a symmetric and an asymmetric mode is logically expected. Our simulation results confirm this issue as illustrated in Fig. 2. Both modes consist of the surface plasmon (SP) modes at the metallic interface of the core-shell structure coupled to the guided modes of the semiconductor nanorods.

Our studies reveal that in such symmetric structures the symmetric hybrid plasmonic mode has much lower propagation loss than the asymmetric one. For example, for h = 5 nm, the symmetric mode has a propagation loss about five times lower than the asymmetric mode. So, we only investigate the symmetric hybrid mode as the main propagating mode in the presented structures. Fig. 2 (a) and (b) shows the 2D E_x field distributions of the symmetric and asymmetric hybrid plasmonic modes, respectively, for r_2 = 50 nm and h = 10 nm. Fig. 2 (c) and (d) shows the 1D E_x field distributions of the symmetric and asymmetric modes along the horizontal dash-dotted lines in Fig. 2 (a) and (b), respectively. The standing-wave pattern of the electric field which is formed by the SIMIS based FP cavity is depicted in Fig. 2(e) and (f) for r_2 = 50 nm and h = 10 nm in the y = 50 nm plane and the waveguide/air interface is located at $z \approx 0.68$ μm.

The absolute normalized electric field of the symmetric mode which demonstrates the confinement of the field, is presented in Fig. 3 for h = 5 nm and r_2 = 50 nm. As can be seen in Fig. 3 (a), the hybrid mode is mainly localized within the insulator spacer region. Fig. 3 (b) and (c) show the distribution of the x and y components of the electric field

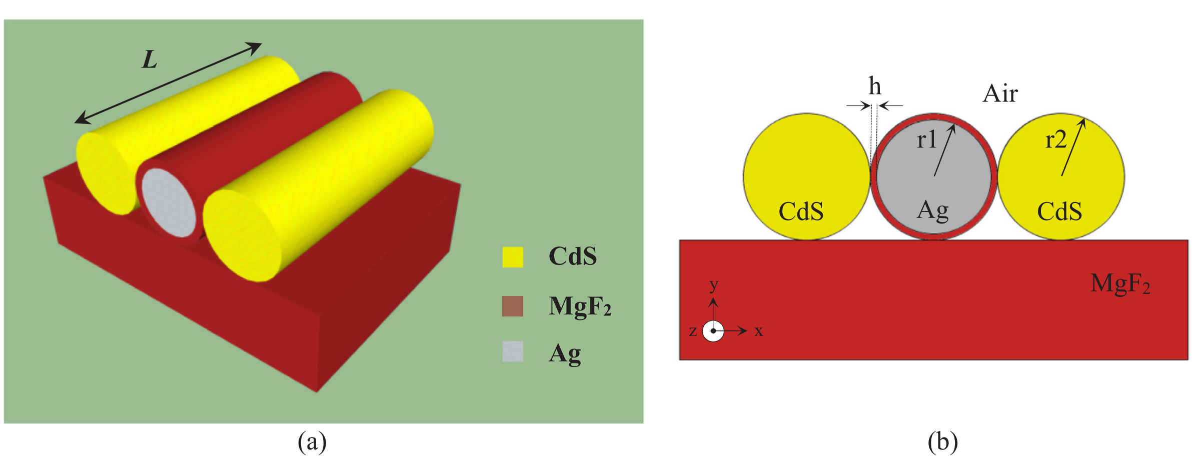

Fig. 1. (a) Three dimensional schematic of the SIMIS based spaser (b) Cross-sectional view of the SIMIS structure.