نانولیزر پلاسمونیکی مبتنی بر نانومیله، جهت استفاده به عنوان منبع پلاسمونی تعبیه شده در موجبر

محمد حسین مطوس و عباس ظریفکار

ایران، فارس، شیراز، بولوار زند، دانشگاه شیراز، دانشکده مهندسی برق و کامپیوتر، بخش مخابرات و الکترونیک

چکیده - یکی از موانع کاهش ابعاد لیزرها حد پراش است که در یک بعد، تقریبا برابر نصف طول موج انتشار یافته توسط لیزر می‌باشد. پژوهشگران در سال های اخیر با استفاده از پلاسمون سطحی موفق به غلبه بر حد پراش شده‌اند و این خاستگاه طراحی نانولیزرهای پلاسمونیک یا همان اسپیسرها می باشد. یکی از مشکلات پیش‌رو، راندمان تزویج کم اسپیسرها است که با استفاده از پیکربندی منبع پلاسمونیک تعبیه شده در موجبر یا کاواک درون خط تا حدودی قابل حل است. از این‌رو در این پژوهش یک نانولیزر پلاسمونیکی مبتنی بر ساختار موجبری نیمه هادی – عایق – فلز – عایق – نیمه هادی با قابلیت استفاده به عنوان منبع پلاسمونی تعبیه شده در موجبری متشکل از سه نانومیله ی جفت شده، طراحی و بررسی شده است. شبیه‌سازی‌های انجام شده به روش اجزاء محدود نشان می‌دهند که اضافه کردن یک نانومیله نیمه هادی به نانولیزر پلاسمونیکی پیشنهاد شده ی پیشین، عملکرد مناسب‌تری را به ارمغان می‌آورد. به عنوان مثال ساختار جدید در شعاع ۴۰ *nm* و ضخامت عایق بیشتر از ۷/۸ *nm*، همزمان آستانه و پهنه مد بهنجار شده کوچکتری دارد که آن را به عنوان منبع نوری تعبیه شده در موجبر مناسب می سازد.

کلید واژه- اسپیسر، نانولیزر پلاسمونیکی، نانوکاواک‌های تعبیه شده در موجبر، نانومیله های جفت شده

An Appropriate Nanorod-Based Plasmonic Nanolaser for Utilizing as a Waveguide-Integrated Plasmon Source

Mohammad Hossein Motavas and Abbas Zarifkar

Department of Communications and Electronics, School of Electrical and Computer Engineering, Shiraz University, Shiraz, Iran

Abstract- One of the leading obstacles in scaling down semiconductor lasers in all three dimensions is the diffraction limit. Experimental results show that plasmonic cavities can overcome this great challenge. However, one of the main problems is how to utilize these structures more efficiently as integrated devices in optoelectronic and plasmonic circuits since they have low coupling efficiency. One solution is to benefit metal-insulator-semiconductor (MIS) nanostructures with inline or waveguide-integrated nanocavities to achieve higher coupling efficiency. In this paper, a plasmonic nanolaser based on semiconductor-insulator-metal-insulator-semiconductor (SIMIS) nanostructure is proposed and investigated. This structure is suitable for utilizing as a waveguide-integrated nanocavity in a hybrid plasmonic waveguide based on coupled nanorods. Simulation results based on the finite element method (FEM) show that the presented structure with a radius of 40 nm and insulator layer thickness of more than 8.7 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. So, the SIMIS based spaser may result in a proper performance as a waveguide-integrated plasmon source.

Keywords: Coupled nanorods, plasmonic nanolaser, spaser, waveguide-integrated nanocavities.

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M. H. Motavas
m.motavas@shirazu.ac.ir

A. Zarifkar
zarifkar@shirazu.ac.ir

1 Introduction

The concept of spaser was explained by Bergman and Stockman in 2003 [1]. A successful laboratory sample of SPP-based spaser or plasmonic nanolaser was created by Oulton et al. at the lasing wavelength of 490 nm [2]. 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. The semiconductor nanorod acts as the gain medium and its end facets form a microscale Fabry–Pérot cavity [3]. In 2010, Zhu investigated the modal properties of this MIS structure at the same wavelength [4]. Similar MIS based structures have also been presented in recent years [5]. The idea of using more than one nanorod in a MIS waveguiding structure was proposed by Bian et al. in 2012 [6]. After that, they introduced a 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 [7]. Despite significant advances in design and fabrication of spasers, their integration within practical optoelectronic and plasmonic circuits remains a challenging issue due to inefficient coupling to waveguides. To resolve this problem, one can utilize waveguide-integrated or in-line nanocavities [8]. It is shown that utilization of a planar waveguide-integrated nanoscale plasmon source can realize high coupling efficiency of ~60% and a small footprint of $\sim 0.06\ \mu m^2$ which is suitable for dense integration [9]. In this work, we propose and analyze a nanorod based plasmonic nanolaser with semiconductor-insulator-metal-insulator-semiconductor (SIMIS) structure. Although there is a compromise between the normalized mode area and the lasing threshold, by adding an extra semiconductor nanorod as a gain medium to a MIS structure, we can achieve a lower normalized mode area and at the same time, a lower threshold. So, the presented nanolaser has the capability of using as a practical SPP source due to its proper characteristics. The remainder of this paper is organized as follows. In section 2, the structure of nanolaser is introduced. In section 3, the simulation results are presented and analyzed. The paper is concluded in section 4.

2 The Plasmonic Nanolaser Structure

The three dimensional schematic of our proposed spaser and its cross-sectional view are shown in Fig. 1 (a) and (b), respectively. As shown in this figure, 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 [7]. The distance between the 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 length of three nanorods is 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 plasmonic nanolaser is 490 nm [2]. At this wavelength, the refractive indices of Ag, MgF_2 and CdS are 0.05+3.039i, 1.4 and 2.4, respectively.

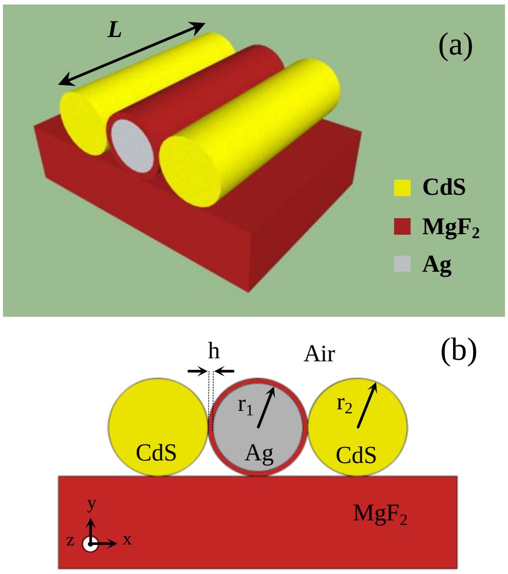

Figure 1: (a) Three dimensional schematic of the spaser (b) Cross-sectional view of the SIMIS structure.

3 Simulation Results and Analysis

In this section, first we obtain the electric field distribution at the device cross section which is shown in Fig 2 (a).

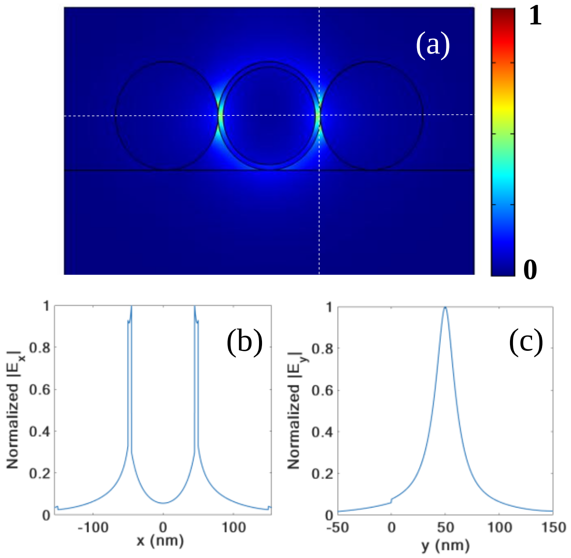

Figure 2: Normalized electric field (a) cross section distribution (b) x component (c) y component of propagated hybrid plasmonic mode in SIMIS structure.

This hybrid mode consists of the surface plasmon mode of the core-shell structure coupled to the guided modes of the semiconductor nanorods. As can be seen in Fig. 2(a), the hybrid mode is localized within the insulator spacer region. Fig 2(b) shows that the lateral coupling between the metallic core and the semiconductor nanorods causes significant field enhancement in the gap region and confines the x component of the electric field in this area. The y component of the electric field is shown in Fig. 2(c). The hybrid plasmonic mode characteristics include the mode effective index (n_{eff}), the effective propagation loss (α_{eff}), the confinement factor (Γ), and the normalized mode area (A_{eff}/A_0) [4, 7]. These characteristics in our proposed nanlolaser are shown in Fig. 3 (a) to (d), respectively, for three different values of r_2. As seen in Fig. 3 (a) and (b), the mode effective index and the propagation loss show minimum values at a given *h*.

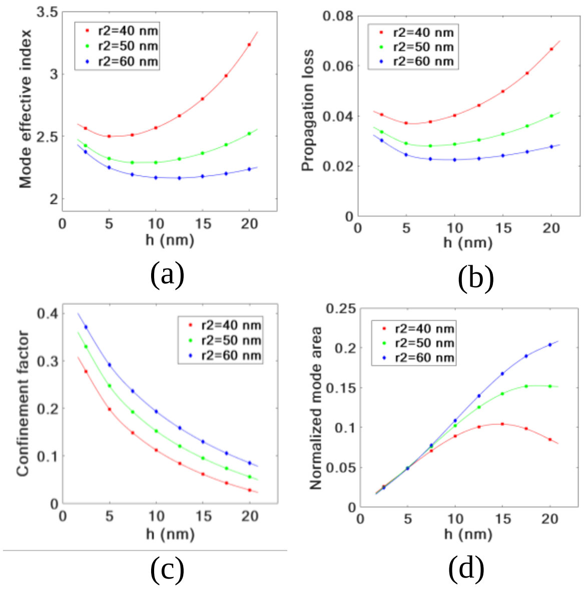

Figure 3: (a) Mode effective index (b) Propagation loss (c) Confinement factor (d) Normalized mode area of hybrid plasmonic mode in SIMIS structure.

In fact, there are two phenomena that affect n_{eff} and α_{eff}. The first one is the optical coupling between two nanorods which weakens by increasing *h* and is dominant at relatively small distances. The second one is the confinement of the electric field around the metallic core surface. When *h* increases, the latter phenomenon is dominant since the core becomes relatively small compared to *h*. On the other hand, when *h* increases, the overlap between the hybrid mode and the gain region decreases which in turn causes that the confinement factor be reduced as shown in Fig. 3 (c). The decrease of spatial confinement of the hybrid plasmonic mode will lead to increment of the effective mode area and consequently the normalized mode area as shown in Fig. 3 (d). However, for larger *h* values, the electric field is more confined around the metallic core which causes that the normalized mode area to be decreased. The calculation of lasing threshold, g_{th}, in these kinds of nanorod based spasers is explained by L. Zhu in 2010 [4]. Fig. 4 depicts the lasing threshold in our study as a function of *h* for *L* = 30 μm and three different values of r_2.

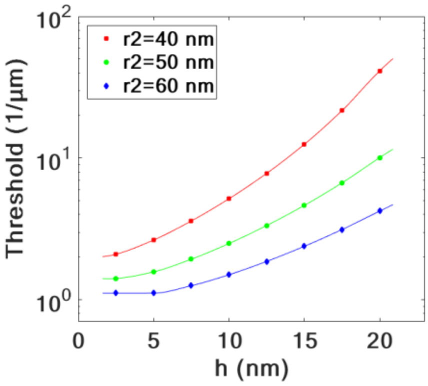

Figure 4: Lasing Threshold of SIMIS based spaser as a function of h for L = 30 μm and three different values of r2.

By increasing *h*, the propagation loss increases and the confinement factor decreases, so the lasing threshold will increase. In fact, when the overlap between the hybrid mode and the gain region decreases, the effect of propagation loss will increase that leads to increment of the lasing threshold of the hybrid plasmonic mode. According to the simulation results, by selecting proper geometric parameters as r_2 = 40 nm and *h* = 16 nm, the lasing threshold and the normalized mode area of the SIMIS-based nanolaser can reach 14.7 μm^{-1} and 19.3, respectively, which are relatively lower than the corresponding parameters of the MIS-based plasmonic nanolaser in Ref. [7]. Therefore, our results show that adding an extra semiconductor nanorod to the prior MIS structure is a reasonable way for using the proposed nanolaser as a waveguide-integrated plasmon source.

4 Conclusion

In conclusion, a plasmonic nanolaser based on semiconductor – insulator – metal – insulator – semiconductor structure can be a suitable choice for on chip applications. In fact, the presented SIMIS naorod based nanocavity, with the capability of being used as an in-line nanocavity, shows better threshold and mode effective area in comparison with the MIS-based nanolasers. This is accomplished by adding an extra semiconductor nanorod to metal-insulator-semiconductor structure.

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