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An Ultraviolet Hybrid Plasmonic Waveguide for Nanolaser Applications

Zhiquan Li[1], Yajuan Wang[1], Jiahuan He[1], Dandan Feng[1], Erdan Gu[1], Wenchao Li[2]

[1]Institute of Electrical Engineering, Yanshan University, Qinhuangdao, China
[2]School of Control Engineering, Northeastern University at Qinhuangdao, Qinhuangdao, China
Email: lzq54@ysu.edu.cn

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Abstract

In this paper, a novel hybrid plasmonic waveguide with a metal ridge and an MgF2 dielectric layer is demonstrated at ultraviolet band. We investigate the propagation distance, the scaling factor and the figure of merit by using the finite element method. The structure enables low scaling factor and long propagation distance. Compared to the previous structure with a metal plate, this waveguide has better performance. And the structure can be used as a nanolaser and has broad application prospects in optoelectronic integrated circuits, biological detection and so on.

Keywords

Ultraviolet, Plasmonic, Waveguide

1. Introduction

In recent years, surface plasmons are introduced to break diffraction limit of waveguide, whose size must be larger than the half wavelength of the optical field in all three dimensions [1]. In this way, plasmonic waveguide can reach subwavelength optical confinement [2] by using the surface plasmon polaritons, which are Transverse Magnetic (TM) polarized surface wave propagating along metal-dielectric interfaces [3]. Therefore, various types of plasmonic waveguide have been presented, such as metal-insulator-metal (MIM) [4], long-range SPP (LSPP) [5], metallic nanowire [6] waveguides and hybrid plasmonic waveguide [7]. However, the previous reports on plasmonic waveguide almost achieved at visible and infrared region because of the lower metal absorption [8]. From the developing trend of the lasing, the main direction goes forward to short wavelength [9], such as ultraviolet band. It benefits to increase storage density of optical information and bandwidth of optical communication [10] [11]. In addition, the ultraviolet resonance Raman spectroscopy is an important means to detect biological molecules [12]. In this paper, we propose a novel hybrid plasmonic waveguide at ultraviolet band. The structure shows tight field confinement and long propagation distance, and reaches deep sub-wavelength-scale. The design has promising potential for application in nanolaser, plasmonic systems and biological detection.

2. Structural Design and Simulation

The geometry of the proposed waveguide is shown in **Figure 1(a)**. The structure consists of a Al metal ridge, a

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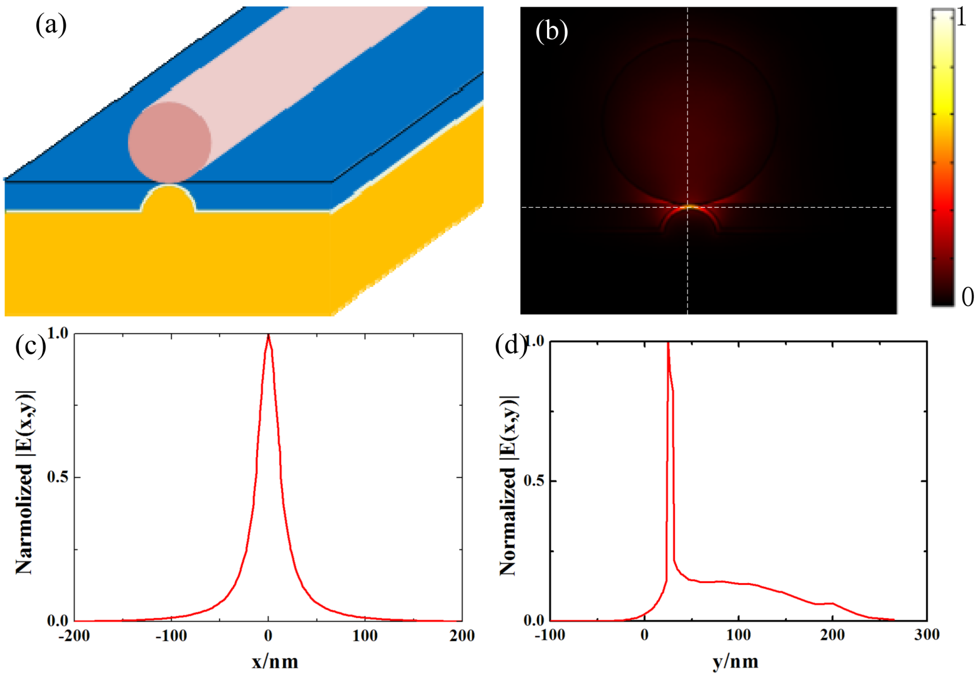

Figure 1. (a) Geometry of the proposed waveguide; (b) Normalized electric field distribution of the fundamental hybrid plasmonic mode of the proposed structure; (c) and (d) Normalized electric field distribution along the horizontal and vertical dashed lines in (b) ($r = 80\text{nm}$).

low-index MgF_2 dielectric layer, a SiO_2 layer and a high-index GaN nanowire. The width of the metal layer is 300 nm, and its height is 100 nm. The length of the GaN nanowire *L* is 30 μm, its radius is *r*. The radius of the metal ridge is fixed at 35 nm. The thickness of the MgF_2 dielectric layer is 5 nm. At the working wavelength of 370 nm, the refractive indices of Al, MgF_2, SiO_2 and GaN are 0.38829 + 4.3466i, 1.3856, 1.46 and 2.65, respectively [11] [13].

Figure 1(b) shows the electric field distribution of the fundamental hybrid plasmonic mode of the proposed structure, where the geometric parameters are chosen as $r_1 = 35\text{nm}$, $r_3 = 80\text{nm}$, $t = 5\text{nm}$. The field enhancements in the horizontal and vertical directions are shown in **Figure 1(c)** and **Figure 1(d)**, respectively. By introducing a metal ridge and the filmy MgF_2 dielectric layer into the design, the electric field energy is concentrated in a tiny area.

To quantify the mode properties, we introduce the indices of the mode scaling factor (SF) and the propagation distance (*D*) [14]. The SF is calculated as the ratio of the effective mode area to the diffraction-limited mode area. It represents the confinement ability for the mode field which is expressed [14] as

$$SF = A_{eff} / A_0 \tag{1}$$

Here, the effective mode area A_{eff} and the diffraction-limited mode area A_0 are expressed by using the following formulas [15]:

$$A_{eff} = \left(\iint |\mathrm{E}|^2 dxdy\right)^2 / \left(\iint |\mathrm{E}|^4 dxdy\right) \tag{2}$$

$$A_0 = \lambda^2 / 4 \tag{3}$$

In the above expressions, *E* is the electric field intensity of the hybrid mode and λ is the working wavelength. The propagation distance (*D*) is defined as [11]

$$D = \frac{1}{2\,\mathrm{Im}(\beta)} \tag{4}$$

where β is the mode propagation constant.

The **Figure 2** shows the effect of the nanowire radius(r) on the performances of the structure. Obviously, the mode scaling factor firstly decreases before increaseing while the propagation distance declines with the nanowire radius increasing. When the nanowire radius approaches the metal rib radius, the mode scaling factor achieves the minimum value 0.0194. In the case, the effective mode area is $0.00485\lambda^2$. The larger nanowire radius leads to larger propagation distance, but larger mode scaling factor. So it is meaningful to define the figure of merit (FOM), which is given by [14]

$$FOM = \frac{D}{SF} \tag{5}$$

The lager FOM indicates better performance of a waveguide. The **Figure 3** shows the FOM with the nanowire radius increasing firstly increases before decreasing. The maximum value 28.56 μm is obtained at $r = 80\text{nm}$. In addition, it indicates the FOM of the present structure is larger than that of previous structure with a metal plate [12], owing to the metal ridge and the filmy MgF_2 dielectric layer.

The pump threshold is the minimal value the gain reaches when achieving lasing action. It is related to the nanowire length L and the end facet reflectivity R. The R [16] is expressed by the following equation:

$$R = (n_{eff} - 1)/(n_{eff} + 1) \tag{6}$$

The lasing threshold is calculate [16] by

$$Gth = (k_0 \partial_{eff} + \ln(1/R)/L)/\Gamma * (n_{eff}/n_{wire}) \tag{7}$$

where $k_0 = 2\pi/\lambda$, n_{wire} is the refractive index of the gain nanowire, and n_{eff}/n_{wire} is the enhancement part of the modal effective index. **Figure 4** shows that the pump threshold of the proposed waveguide increases with enlarging r. Its minimum is $0.328 \times 10^3 \text{cm}^{-1}$.

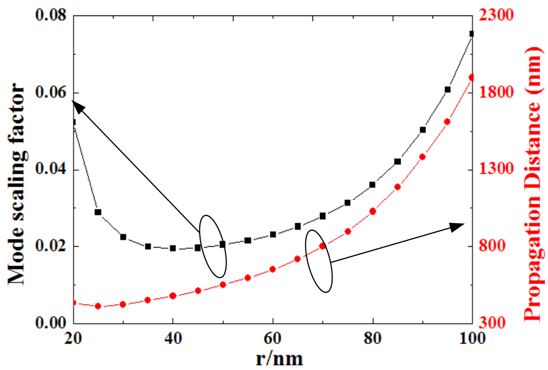

Figure 2. The *SF* and *D* of the fundamental hybrid plasmonic mode with different *r*.

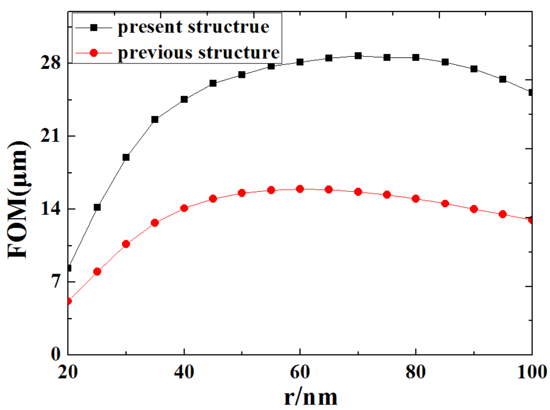

Figure 3. The *FOM* of the fundamental hybrid plasmonic mode of present structure and previous structure with different *r*.

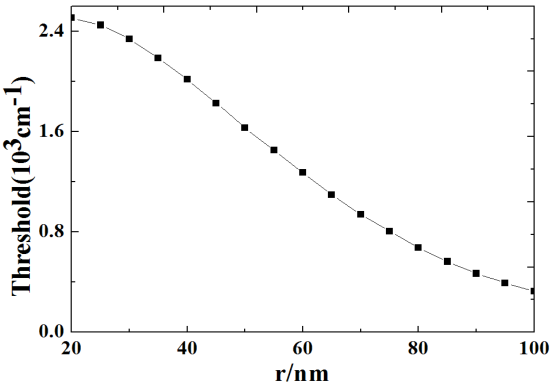

Figure 4. The pump threshold of the fundamental hybrid plasmonic mode of present structure with different *r*.

3. Conclusion

We present a new type of ultraviolet waveguide based on surface plasmons which attains deep-subwavelength scale and has long propagation distance. By using the COMSOL Multiplicity software, we investigate the light field distribution, and analyze the effect of the radius of the gain medium nanowire on the properties and the lasing threshold. The results show that the larger nanowire radius causes the better performance of the proposed waveguide. So we can select the optimal radius of the nanowire as 80 nm. In this case, the *SF*, the *D* and the threshold are 0.0359, 1027.3nm and $0.67\times10^{3}\text{cm}^{-1}$, respectively. Compared to the previous ultraviolet waveguide with a metal plate, the performance of the present structure with a metal redge is improved significantly with the same geometric parameters. The designed structure offers a new idea for the high-density photonic integrated devices, such as the deep-subwavelength-scale ultraviolet nanolaser.

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