Gain-assisted indented plasmonic waveguide for low-threshold nanolaser applications*

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A subwavelength plasmonic indented waveguide with an active InGaAsP core is proposed. The characteristics of the gap plasmon mode and gain required for lossless propagation are investigated and analyzed by the finite element method. We numerically calculate the normalized mode areas and percentages of energy confined in InGaAsP and metal for plasmonic nanolaser applications. It is shown that the indentation of the sidewalls has an optimal value for which the lasing threshold gain is minimal. The structure could enable low-threshold subwavelength lasing and applications for optoelectronic integrated circuits.

Keywords: optical waveguide, nanolasers, surface plasmon, gain

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1. Introduction

The desire for high speed, compact, and localized coherent light components, detectors, and modulators has motivated a rapid expansion of research into nanophotonics. The use of surface plasmon polaritons (SPPs) is one of the most feasible ways to break the diffraction limit for routing and manipulating light in nanoscale.[1−4] As a result, the development of nanolasers based on SPPs is motivated for integration with silicon-based microelectronic devices and semiconductor-based optoelectronic devices. There have been attempts to overcome metallic loss in plasmonic waveguides to realize nanolasers. The dielectric–metal–dielectric (DMD) waveguides have low loss but weak optical confinements. On the contrary, the metal–dielectric–metal (MDM) waveguides can create subwavelength confinements of optical fields but suffer huge loss arising from metal absorption.[5] Recently, the hybrid plasmonic waveguide[6−9] has been proposed to achieve low loss with acceptable confinement simultaneously, due to the coupling between lossless dielectric waveguide mode and the surface plasmon mode at the metal–dielectric interface. However, for optoelectronic integrated systems applications, an electrical pumped light source is indispensable.[10] To reduce the laser threshold, both low propagation loss and high field confinement in the gain media region are desired.[8] A recent successful demonstration of lasing in electrically pumped MDM subwavelength plasmonic waveguide is demonstrated by Hill.[11,12] In order to improve the performance of active plasmonic devices and to get a better understanding of how light and matter interact, it is significant to investigate the gain character of the system for potential applications of gain-assisted plasmonic structures in optical communication and integrated photonics.[10,13−15] The most recent work about a subwavelength plasmonic laser structure based on an MDM nanocavity has also shown promising application for optoelectronic integrated circuits.[15]

In this paper, based on the waveguide lasing concepts,[9−11] we investigate the characteristics of the MDM surface plasmon gap waveguide (SPGW) with semiconductor gain medium core targeting for subwavelength plasmonic nanolasers with low threshold. Firstly, the properties and gain required for lossless propagation of the gap plasmon mode are investigated and analyzed. Then, the normalized mode area and confinement factor are calculated. Finally, the threshold gain for lasing is demonstrated. We show that

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minimum threshold gain for lasing is achieved at optimal gain region width in indented geometry, rather than conventional MDM geometry with no indented sidewalls. The low threshold property makes the proposed nanolaser a potential candidate for integrated active plasmonic devices.

2. Model and calculation

2.1. Model and optical property

We propose an active SPGW consisting of InP/InGaAsP/InP sandwich layers with rectangular cross section. Figure 1(a) shows the schematic diagram of the waveguide. The InGaAsP layer with height h and width w forms the gain medium. The two sides of the waveguide are coated by silver. The InP claddings are indented equally on the top and bottom of the InGaAsP core. In our following simulations, the wavelength is fixed at 1550 nm. The minimum value of the thickness of silver is 50 nm. The permittivity of the InGaAsP core and the InP claddings are taken as 12.25 and 10.03 respectively.[16] The permittivity of silver is $-129 + 3.3\mathrm{i}$.[17] The width and height of the cladding layer in these structures are all set as 200 nm and 100 nm respectively unless stated otherwise.

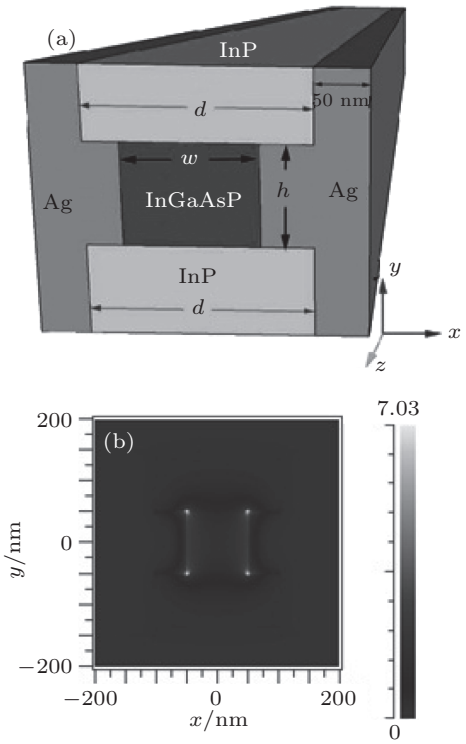


Fig. 1. (a) The schematic diagram of the proposed indented surface plasmon gap waveguide. (b) Total electromagnetic energy density distributions for $[w, h, d] = [100\ \mathrm{nm}, 100\ \mathrm{nm}, 200\ \mathrm{nm}]$.

Figure 1(b) shows the total electromagnetic energy density distributions $W(x, y)$ of the gap plasmon mode for $[w, d] = [100\ \mathrm{nm}, 200\ \mathrm{nm}]$ at $h = 100$ nm, calculated by using the following formula

$$W(x,y) = \frac{1}{2}\left[\mathrm{Re}\left(\frac{\mathrm{d}(\varepsilon(x,y)\omega)}{\mathrm{d}\omega}\right)|E(x,y)|^2 + \mu_0|H(x,y)|^2\right]. \quad (1)$$

Here, $|E(x, y)|^2$ and $|H(x, y)|^2$ are the intensity of electric and magnetic fields respectively. The SPWG with indented sidewalls has strong energy confinement and optical field overlap with the gain medium. Strong optical confinements in vertical and horizontal directions are achieved by utilizing an index guiding scheme and the metal confinement effect of the sidewalls. The nanoscaled gap can confine and store electromagnetic energy in subwavelength scales. Structures with indented sidewalls show the advantage of confining light in the gain medium, which is important for active components.

Figure 2(a) shows n_{eff}, the real part of the mode effective index $N_{\mathrm{eff}} = \beta/K_0$ of the gap plasmon mode with different core heights, and the core width w, varying from 20 nm to 200 nm. K_0 represents the free space wave vector. For a fixed waveguide core height, the effective index n_{eff} decreases as the core width increases, due to the decrease of the optical confinement. The effective index changes insensitively for different heights, which can be explained by the strong optical confinement induced by metallic sidewalls. The corresponding propagation length is calculated as $L_{\mathrm{m}} = 1/2\,\mathrm{Im}\,(\beta)$. High propagation loss in SPGW leads to a relatively short propagation length. The result reveals the fundamental trade-off between the size of the plasmonic waveguide and its propagation length. As the width w approaches the cladding width d, the propagation length does not change seriously, because the mode performs more like the symmetric SPP mode in MDM slab waveguide. The effective mode area can be adopted to represent the optical field confinements,

$$A_{\mathrm{eff}} = \iint W(x,y)\,\mathrm{d}x\,\mathrm{d}y/\max(W(x,y)), \quad (2)$$

which is defined as that in Ref. [6]. The SPGW could have an ultrasmall effective mode area, as shown in Fig. 2(b). For example, for 100 nm × 100 nm InGaAsP core, the normalized effective mode area is only about $1 \sim 2$ orders of magnitude smaller than the diffraction-limited area in free space $A_0 = \lambda^2/4$. Increase of the height h leads to only slight increase of the effective

area. This indicates good vertical confinement of the mode for the design of indented sidewalls, compared to slab waveguide with no indented sidewalls. Due to the strong confinement of waveguide with indented sidewalls, a steady portion of energy is maintained in the gain region, which is desired for overcoming loss of active plasmonic devices.

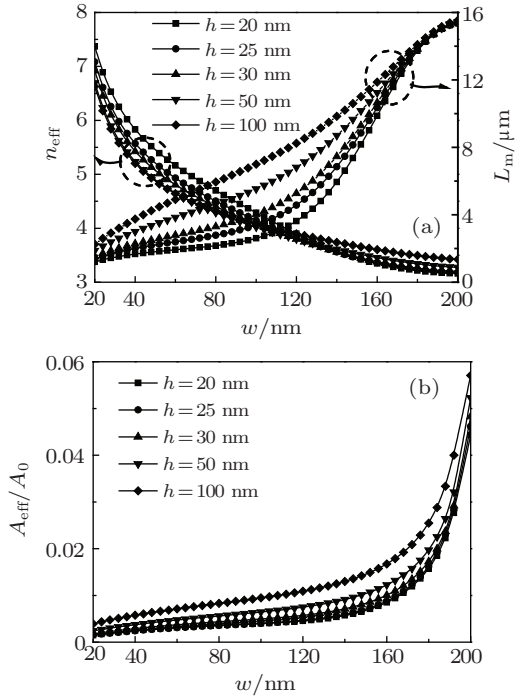


Fig. 2. (a) The effective index $n_{\rm eff}$ and propagation length $L_{\rm m}$ of the gap plasmon mode versus width w of the gain medium for different heights. (b) The normalized mode area $A_{\rm eff}/A_0$.

2.2. Gain assisted propagation and threshold properties for plasmonic waveguide-based nanolaser

The loss as an important parameter for active device designs and applications will have remarkable influences on the threshold gain for lasing, which becomes more important for semiconductor nanolasers at subwavelength scales. Before examining the threshold gain for lasing, the threshold gain required for lossless propagation[18,19] of the geometry is calculated, corresponding to the image part of the effective mode index $\mathrm{Im}\,(N_{\rm eff}=0)$.

The result shown in Fig. 3(a) implies that low gain value for lossless propagation can be achieved by choosing an appropriate size of the waveguide gain medium. One can see that the gain value increases as the height of the gain medium decreases. However, the gain required for lossless propagation does not undergo a monotonic change when the gain medium widths increase, especially for heights of a few tens of nanometers. At first, the gain medium core size is of tens of nanosize, thus more gain is required for lossless propagation. Although with increased width of gain core, loss in metal dominates and leads to the increased gain value. Finally, the core width is increased to the same as the cladding width, where no indentation exists and slab-like MDM geometry is formed. Poor confinement along with less mode overlap with the gain region and huge sidewall metal loss is supposed to work together and finally leads to the secondly increased gain value.

The energy ratio $R_{\rm Ag/InGaAsP}=P_{\rm Ag}/P_{\rm InGaAsP}$ is calculated to understand the extraordinary features shown in Fig. 3(a), where $P_{\rm InGaAsP}$ and $P_{\rm Ag}$ are the proportions of energy confined in the InGaAsP gain region and metal. The result is plotted in Fig. 3(b). By comparing the cases in Fig. 3(a) and Fig. 3(b), the trends of them are consistent with each other, which gives the explanation for how the gain value required for lossless propagation evolves.

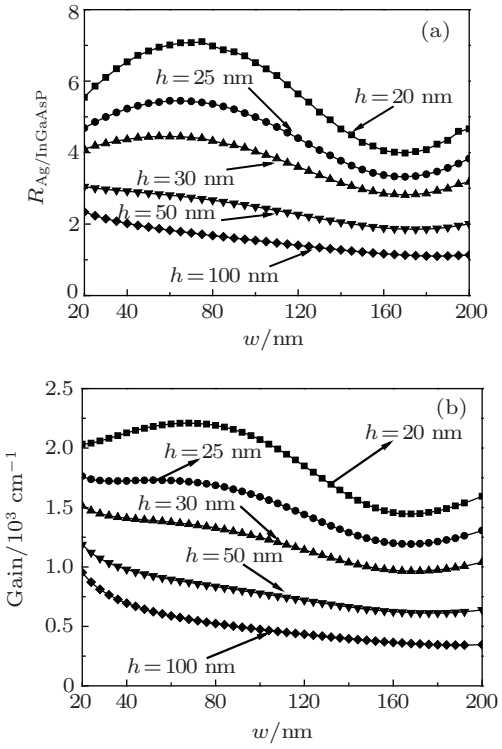


Fig. 3. (a) The threshold gain required for lossless propagation of the gap plasmon mode. (b) The ratio between the energy proportions in Ag and InGaAsP for different gain region heights and widths.

The facet reflectivity R is estimated by $R=(n_{\rm eff}-1)/(n_{\rm eff}+1)$. Assuming the length of the waveguide L to be 20 μm, the threshold gain for lasing is

calculated[8,20] by

$$G_{\rm th} = 1/\Gamma_{\rm E}(K_0\alpha_{\rm eff} + \ln(1/R)/L)(n_{\rm eff}/n_{\rm wire}). \quad (3)$$

The simple approximation of the facet reflectivity is adopted to illustrate the geometric parameters' influence on the lasing gain properties rather than predict the accurate value of the material gain. Here $\alpha_{\rm eff}$ represents the effective propagation loss. $n_{\rm wire}$ is the refractive index of the gain medium. The factor $n_{\rm eff}/n_{\rm wire}$ indicates the modal effective index enhancement and the factor $\Gamma_{\rm E}$ denotes the ratio of electric energy confined in the gain region.[21,22] Here the gain properties of the system are calculated at a fixed wavelength; for real accurate threshold gain value, the dispersion nature of silver and the gain medium should be taken into account.

The dependence of the threshold gain on gain medium width of the proposed nanolaser is investigated. The results in Fig. 4(a) indicate that minimum threshold gain required for lasing could be achieved with optimal gain region width w of indented geometry due to the enhanced optical confinement.

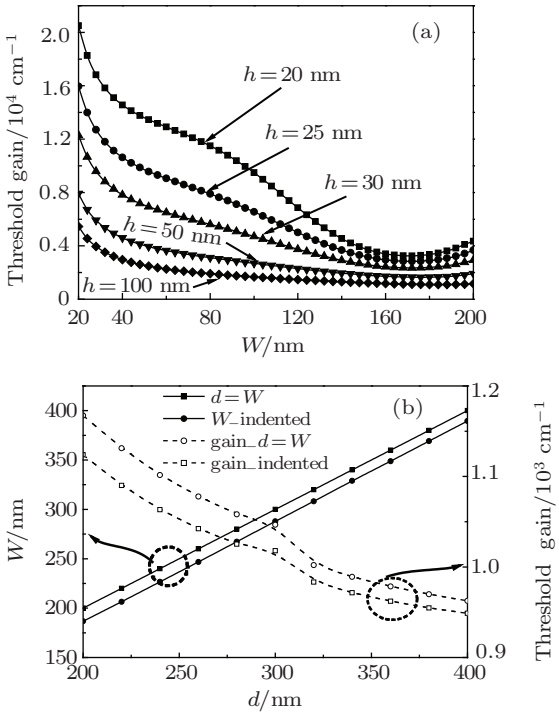


Fig. 4. (a) The threshold gain value for lasing versus widths of the gain medium, for the cases of InGaAsP height h = 20 nm, 25 nm, 30 nm, 50 nm, and 100 nm. (b) Optimum values of gain medium width and the corresponding minimum threshold gain for lasing versus different cladding widths for the case of InGaAsP height h = 100 nm.

For example, for the gain medium height h = 20 nm, the threshold gain required for lasing in the waveguide without indented sidewalls is calculated to be about 4355 cm^{-1}, and the lowest value of waveguide with indented sidewalls is about 3251 cm^{-1}. A decrease of 1104 cm^{-1} of the threshold gain is achieved by employing the nanoscale indentation.

The results in Fig. 4(b) show the optimum values of gain medium width $w_{\rm indented}$ and the corresponding minimum threshold gain for lasing gain$_{\rm indented}$ at different cladding widths. The optimum values of the gain medium width increase linearly as the cladding widths increase from 200 nm to 400 nm. Obvious decrease of the threshold gain for lasing can be seen in the structure with sidewalls indentation. This is promising for finding an application to reduce the threshold gain for semiconductor nanolaser with MDM waveguide geometry. Nano-fabrication techniques such as epitaxies, electron beam lithography, dry etching, and various material deposition techniques can be used to fabricate the waveguide.[11,12]

We note that the indented SPGW-based laser structure proposed here possesses low lasing thresholds and notable optical confinement for applications in an active plasmonic system.

3. Conclusion

We have proposed an active surface plasmon gap waveguide with indented metallic sidewalls targeting for plasmonic nanolasers with low-threshold operation. We analyze the effect of the indented sidewalls on the gain value required for lossless propagation. We find that the indentation of the sidewalls has an optimal value to minimise the lasing threshold gain, due to the enhanced optical confinements of indented metallic sidewalls. The proposed nanolaser is promising for finding many applications in integrated optoelectronic and active plasmonic system.

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