Optics Communications 294 (2013) 414–419

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Gain enhancement in a V-shaped plasmonic slot waveguide for efficient loss compensation at the subwavelength scale

Yusheng Bian [a], Zheng Zheng [a,*], Xin Zhao [a], Pengfei Yang [b], Lei Liu [a], Jinsong Zhu [c], Tao Zhou [d]

[a] School of Electronic and Information Engineering, Beihang University, 37 Xueyuan Rd, Beijing 100191, China
[b] Beijing National Laboratory for Condensed Matter Physics and Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China
[c] National Center for Nanoscience and Technology, No.11 Beiyitiao, Zhongguancun, Beijing 100190, China
[d] Department of Physics, New Jersey Institute of Technology, Newark, NJ 07102, USA

ARTICLE INFO

Article history:
Received 24 October 2012
Received in revised form
27 December 2012
Accepted 28 December 2012
Available online 19 January 2013

Keywords:
Waveguide
Surface plasmon
Integrated photonics

ABSTRACT

An active plasmonic slot waveguide comprising an inverted triangular metal wedge incorporated inside a V-shaped plasmonic groove with a low-index gain medium embedded between them is presented, and its guiding properties are investigated numerically at the wavelength of 1550 nm. The presented waveguide is shown to be capable of supporting two fundamental plasmonic slot modes with high field localization to the V-shaped low-index slot region. Due to such strong optical confinement and significant field enhancement, the introduced gain in the slot could effectively compensate the propagation loss of the supported plasmonic modes. It is revealed that for the studied channel plasmonic slot and wedge plasmonic slot modes, notable gain enhancements are observable within a wide range of geometric parameters. For the considered structure with a 10–40 nm-wide slot, the enhancements of gain can be as large as 11%–159% for the CPS mode while 43%–174% for the WPS mode. These values could be further improved by adopting even narrower slots. It is shown that, by introducing a gain medium with coefficients around hundreds of cm^{-1}, the modal loss can be largely or even fully compensated, with a subwavelength mode area achievable simultaneously. These unique features of the studied V-shaped plasmonic slot waveguide might be useful for its potential applications in compact, active plasmonic components.

1. Introduction

The attractive goal of guiding light at the nanoscale has motivated extensive research into novel waveguiding schemes that are capable of breaking the fundamental diffraction limit. Among numerous presented guiding strategies, surface plasmon polariton (SPP) based structures have received particular attention due to their capabilities of offering two-dimensional subwavelength field confinement [1,2], which cannot be easily achieved by employing photonic crystal [3] or high-index dielectric waveguiding counterparts [4]. A number of different SPP waveguiding schemes for subwavelength light confinement have been proposed and demonstrated [5–9]. Among them, the triangular metallic groove and wedge and their corresponding channel plasmon polariton (CPP) [9–16] and wedge plasmon polariton (WPP) mode [17–20] respectively, have been intensively investigated for their capability to simultaneously provide tight light confinement and low propagation loss. Due to their relatively simple configuration, a number of experimental demonstrations have also been enabled [11,12,17,19,21,22].

Previous studies have reported several types of CPP and WPP based waveguides with different configurations. The conventional CPP waveguide typically consists of a sharp-angled groove milled on a near-infinite-thick metallic substrate. The grooves can be either exposed directly to air [11,12] or filled with dielectric material [23,24]. By changing the infinite metal surface into finite-thick metallic layer, the guiding properties of the waveguide can be greatly modified [25,26], which shows the feasibility to simultaneously support CPP and WPP modes in a single configuration. Here in this paper, we would like to look into an alternative structure that can be somewhat regarded as a reverse type of such a finite-thick CPP waveguide. The presented structure comprises a metal groove substrate separated from a reversed triangular metal wedge by a V-shaped low-index homogenously-thick dielectric layer. Regarding its specific configuration, we here denote it as V-shaped plasmonic slot waveguide. Such a structure can be realized by adopting similar fabrication methods to those of conventional CPP waveguides [12]. For example, after milling a V-shaped groove onto a metal substrate, subsequent deposition of the low-index dielectric layer and the metal wedge can result in a V-shaped slot inside the metal surface. The whole structure can be then covered by dielectric claddings or simply exposed to air. In the following, we carry out detailed investigations on the guiding

* Corresponding author. Tel: + 86 10 82317220.
E-mail address: zhengzheng@buaa.edu.cn (Z. Zheng).

0030-4018/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.optcom.2012.12.091

properties of the plasmonic slot waveguide at the telecom wavelength. Through incorporating gain medium into the V-shaped dielectric slot region, we demonstrate the possibility of effectively compensating the loss of the guided plasmonic modes. It is shown that, owning to the significantly local field enhancement inside the slot region, a giant gain enhancement is attainable. And the overall modal loss can be partially or fully compensated by employing a gain medium with a moderate coefficient.

2. Geometries and modal properties of the plasmonic slot waveguide

Fig. 1 has schematically shown the geometry of the studied plasmonic slot waveguide, where a V-shaped dielectric layer is sandwiched between a metallic groove and reversed metal wedge. Both the groove and the wedge have the same bottom angle θ. The depth of the metal groove is h whereas the top width of the metal wedge is w. The slot width is dictated by the thickness of the V-shaped dielectric layer (t). The bottom tip of the metal wedge has a 10 nm curvature while the corresponding metal groove corner has a radius of $(10+t)$ nm to maintain a constant slot width. The modal properties of the plasmonic slot waveguides are investigated at $\lambda=1550$ nm by the finite-element method (FEM) using COMSOLTM. Scattering boundary conditions along with extremely fine mesh are applied near the slot region to ensure accurate solutions. In the simulations, the cladding and the slot are made of silica (SiO_2), whereas the metal wedge and groove are assumed to be silver (Ag). The permittivities of SiO_2 and Ag are $\varepsilon_c=\varepsilon_s=2.25$ and $\varepsilon_m=-129+3.3i$ [27], respectively.

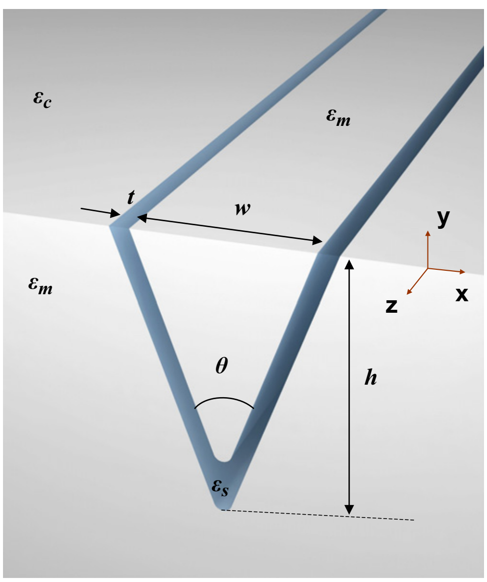

Fig. 1. Geometry of the studied V-shaped plasmonic slot waveguide.

Simulation results indicate the proposed plasmonic waveguide can support two plasmonic slot modes under a wide range of geometric parameters. According to their mode features, they are denoted as wedge plasmonic slot (WPS) mode and channel plasmonic slot (CPS) mode, respectively. For a typical configuration with parameters chosen as: $\theta=25^{\circ}$, $h=600$ nm, $t=20$ nm, the electric field distributions of the supported two fundamental plasmonic slot modes are shown in Fig. 2(a) and (b). It is clearly seen that, for both of the two modes, almost all of the mode power can be stored inside the V-shaped slot region, along with pronounced local field enhancements. For the WPS mode, a substantial portion of the field is distributed at the bottom of the groove, with the maximum electric field amplitude near the metal wedge tip. While for the CPS mode, the field is pushed away from the bottom, getting hybridized with the modes running along the top groove edges at the groove opening.

To gain a comprehensive insight into the modal behavior, we further investigate the modal properties of the two plasmonic slot modes for different slot widths when the groove depth varies from 200 nm to 1000 nm. In the simulations, the bottom angle θ is fixed at 25°. The calculated results of WPS mode and CPS mode are shown in Figs. 3 and 4, respectively. In the figures, N_{eff} is the modal effective index and n_{eff} is the real part of N_{eff}. The propagation length is obtained by $L=\lambda/[4\pi\mathrm{Im}(N_{eff})]$, whereas the effective mode area is calculated using $A_{eff}=(\int\int W(\mathbf{r})dA)^2/(\int\int W(\mathbf{r})^2dA)$. In order to accurately account for the energy in the metal region, the electromagnetic energy density $W(\mathbf{r})$ is defined as [28]:

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

In Eq. (1), $E(\mathbf{r})$ and $H(\mathbf{r})$ are the electric and magnetic fields, $\varepsilon(\mathbf{r})$ is the electric permittivity and μ_0 is the vacuum magnetic permeability. A_0 is the diffraction-limited mode area in free space and defined as $\lambda^2/4$. Normalized mode area can be obtained by calculating A_{eff}/A_0. Normalized optical power (NOPs) is defined as the ratio of the power inside the V-shaped slot region to the total power in the overall

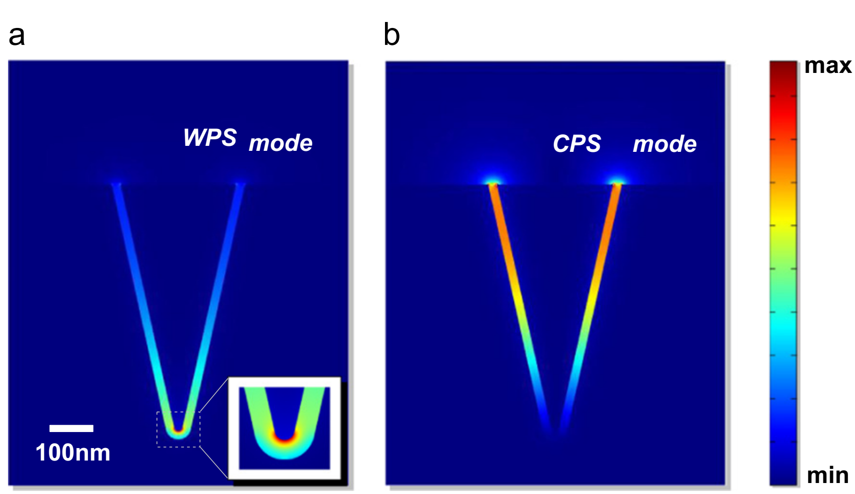

Fig. 2. Electric field distributions of the supported two plasmonic modes ($\theta=25^{\circ}$, $h=600$ nm, $t=20$ nm): (a) wedge plasmonic slot (WPS) mode, where the inset is plotted for better view of the field profile near the metal wedge tip and (b) channel plasmonic slot (CPS) mode.

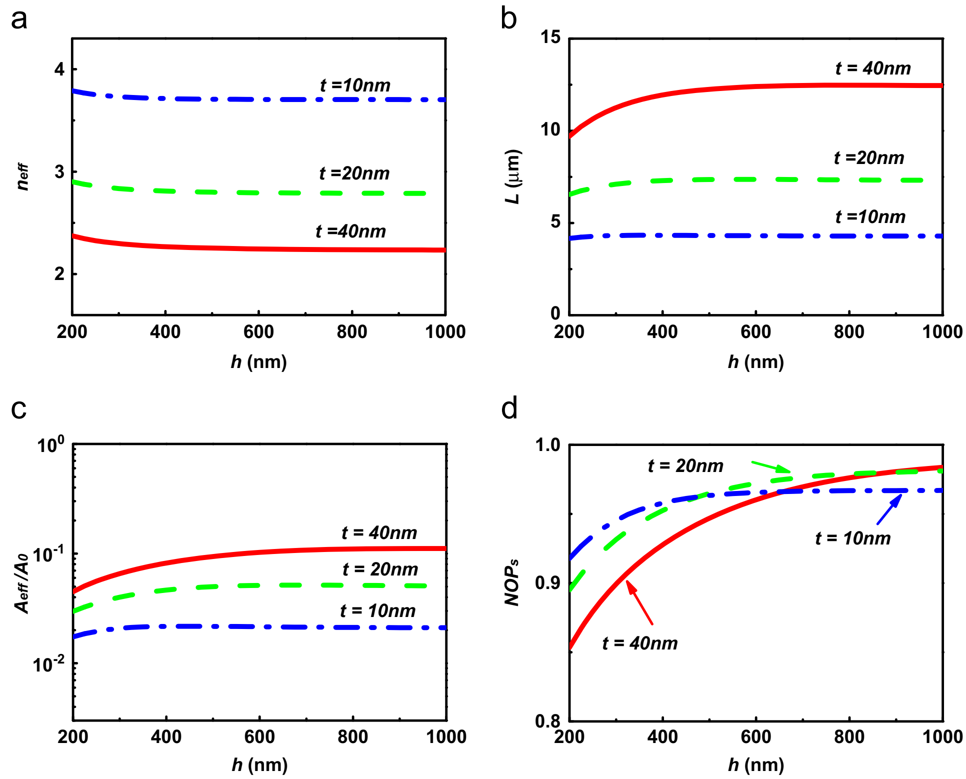

Fig. 3. The WPS mode's properties at different groove depths: (a) modal effective index (n_{eff}); (b) propagation length (L); (c) normalized mode area (A_{eff}/A_0) and (d) normalized optical power in the slot (NOP_s).

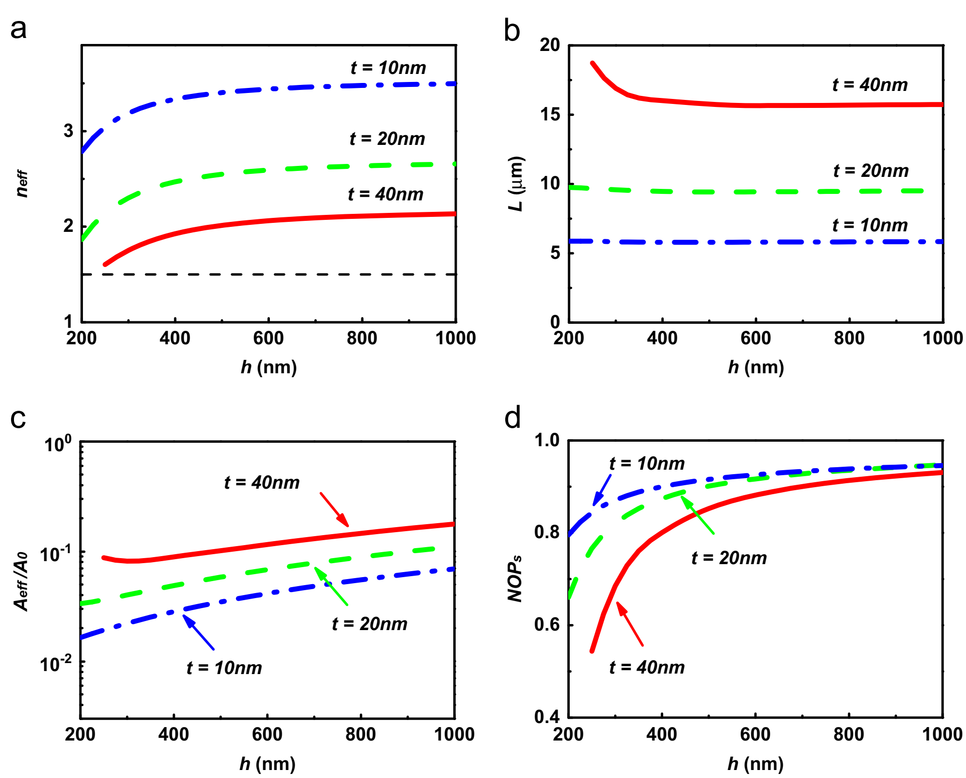

Fig. 4. Dependence of characteristics of the CPS mode on the groove depth: (a) modal effective index (n_{eff}); (b) propagation length (L); (c) normalized mode area (A_{eff}/A_0) and (d) normalized optical power in the slot (NOP_s). The black-dashed line in (a) represents the refractive index of the cladding.

waveguide. It is illustrated in Fig. 3 that for the WPS mode, increasing the groove depth has resulted in decreased modal effective index and reduced propagation loss, along with a larger mode area and more power resided in the slot region. These trends are less significant when the slot width reduces (e.g., see the $t=10$ nm case). Besides, the modal properties remain almost unchanged when the groove depth is relatively large, indicating that the characteristics of the WPS mode are relatively robust against the variation of the metal groove depth when the groove is not too shallow. It is also revealed in Fig. 3(d) that within the considered geometric parameter range, more than 85% of the mode power can be confined in the V-shaped slot area, with a subwavelength mode area achievable simultaneously as seen in Fig. 3(c). On the other hand, the properties of the CPS mode demonstrate a quite different trend (see Fig. 4), where increased modal effective index and propagation loss, larger mode area and NOPs can be observed at larger groove depth. It is also indicated that the CPS mode is more sensitive to the variation of the geometric parameters than the WPS mode. Such a distinction between the modal behaviors is largely due to the different nature of the two modes. The WPS mode field remains highly localized near the metal wedge tip during the changing of the groove depth, which consequently results in relatively stable modal property. By contrast, for the CPS mode, most of its optical power is distributed near-homogeneously inside the upper part of the V-shaped slot, which changes accordingly with the increase of the groove depth. Thus the properties of the CPS mode exhibit a slightly more significant dependence on the h compared to the WPS case. We also note that the CPS mode would be cut-off for large slot width case when h is very small (e.g. $h<250$ nm when $t=40$ nm). As shown in Fig. 4(d), as long as h exceeds 400 nm, more than 80% of the total power can be stored in the slot region for all the studied slot widths. It is also illustrated from Figs. 3(b) and 4(b) that, for both of the studied modes, the propagation lengths do not change dramatically with the variation of the groove depth. Although the propagation losses of both modes are relatively large, yet they can be effectively compensated, through introducing gain medium into the slot region, which we will discuss in the following section.

3. Loss compensation in V-shaped plasmonic slot waveguide

In this section, we investigate the feasibility of compensating the propagation loss of the above two plasmonic slot modes through incorporating gain medium into the V-shaped silica layer of the waveguide. The low-index gain medium can be silica or polymer incorporating quantum dots (QDs) [29], dye molecules [30] or rare-earth materials [31,32]. Based on the feasible fabrication process, taking quantum dots

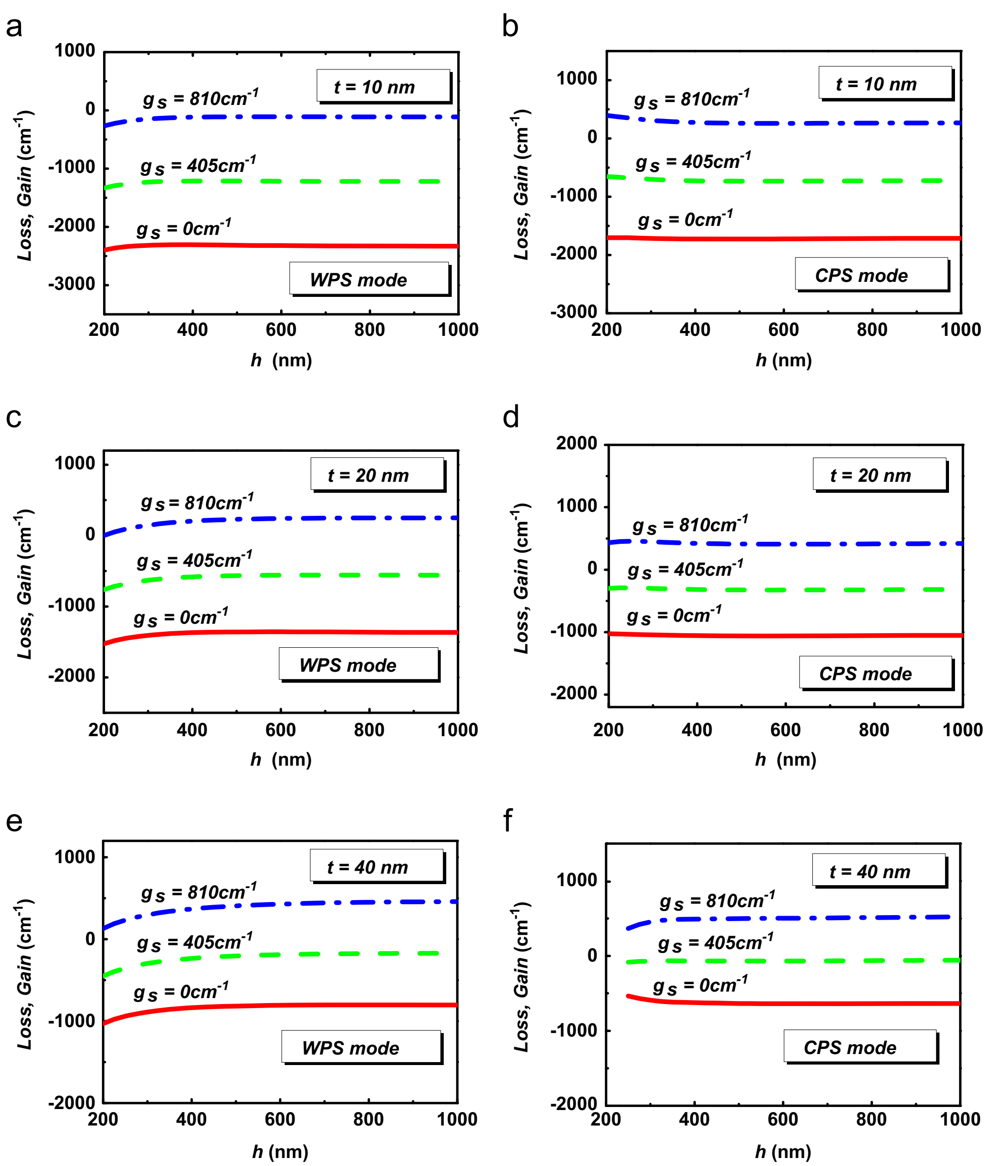

Fig. 5. The modal gain or loss of the WPS and CPS modes for different waveguiding configurations when gain is introduced in the V-shaped slot region: (a,b) $t=10$ nm; (c,d) $t=20$ nm and (e,f) $t=40$ nm.

as an example, by spining coating of a PMMA–QDs solution onto the metal groove, a thin dielectric layer with the gain material can be formed. It is worth mentioning that, for the spin-coating method, the accurate control of the thickness for dielectric layer is more challenging than other deposition process, such as electron beam evaporation technique. Here, the gain coefficient of the bulk material as well as the loss or gain of the overall mode are written in the form of $L=4\pi \mathrm{Im}(N_{eff})/\lambda$ [33,34]. The resultant overall loss or gain of the mode is shown in Fig. 5 under various gain coefficients for different waveguide geometries. Negative and positive values of the vertical coordinates in Fig. 5 illustrate the propagation loss and net optical gain of the modes, respectively. It is clearly revealed that the loss of both plasmonic modes can be reduced as long as gain is introduced. Partial or full compensation of the modal loss could be enabled using material with moderate gain. Even net optical gain is realizable through adopting material with relatively larger gain coefficient. For the same waveguide configuration, since the WPS mode has larger loss than the CPS mode and both of the modes show comparable mode confinement capabilities in the slot region, the compensation of the WPS modal loss typically requires larger material gain as shown in Fig. 5. Similarly, the intrinsic loss for a waveguide with a wider slot is much lower, and consequently it is easier to compensate the loss using a gain material with a moderate coefficient.

Based on the above calculations, we carry out further investigations on the gain enhancements achieved using the proposed V-shaped plasmonic slot waveguides. Here, the enhancement in gain is evaluated by calculating the ratio $\partial g_m/\partial g_s$, where g_m is the gain of the studied plasmonic mode and g_s represents the gain of the material inside the V-shaped slot. From the results shown in Fig. 6(a) and (b), it is clearly seen that enhancements of gain could be attainable for both of the WPS and CPS modes within the studied geometric parameter range, i.e. the ratio $\partial g_m/\partial g_s$ can be larger than 1. This means that it is possible to achieve more gain in the studied plasmonic structure than that attainable in the bulk material (i.e. gain medium inside the slot). The reason for such enhancements are similar to the case of high-index contrast silicon slot waveguide in Ref. [33] and the hybrid plasmonic structure in Ref. [35]. The ratio $\partial g_m/\partial g_s$ can be approximated as a product of the optical power ratio in the gain region and the ratio of the group index to the refractive index of the gain material. Since the optical power ratio in the slot region for the V-shaped plasmonic waveguide can be approaching 1, the giant improvement of the group index over the bulk refractive index would consequently result in a notable gain enhancement. It is noted that, owing to the relatively larger modal overlap with the gain medium in the slot region and stronger field enhancement, the gain enhancement of the WPS mode is slightly larger than that attained in the CPS mode. While such enhancements can be significantly improved by employing narrower slots. It is seen in Fig. 6(a) and (b) that, for the considered structure with a 10–40 nm-wide slot, the enhancements of gain can be as large as 11%–159% for the CPS mode while even 43%–174% for the WPS mode. These enhancements are much larger than those achieved using the active hybrid plasmonic waveguide as reported in Ref. [35]. And it still remains possible to further improve these enhancements values by adopting V-shaped plasmonic slot waveguides with even narrower slots.

In Fig. 6(c) and (d), we show the loss or gain of the WPS and CPS modes sustained by a specific plasmonic slot waveguide when the gain in the slot region gradually increases. Here the groove depth of the waveguide is fixed at 600 nm to ensure a relatively large NOPs and a small modal loss. It is illustrated that the loss or gain increases linearly as gs increases. For the studied cases, the modal loss could be effectively reduced as long as a moderate gain is introduced. When g_s is large enough, the loss of the mode can be fully compensated, which could be found at the

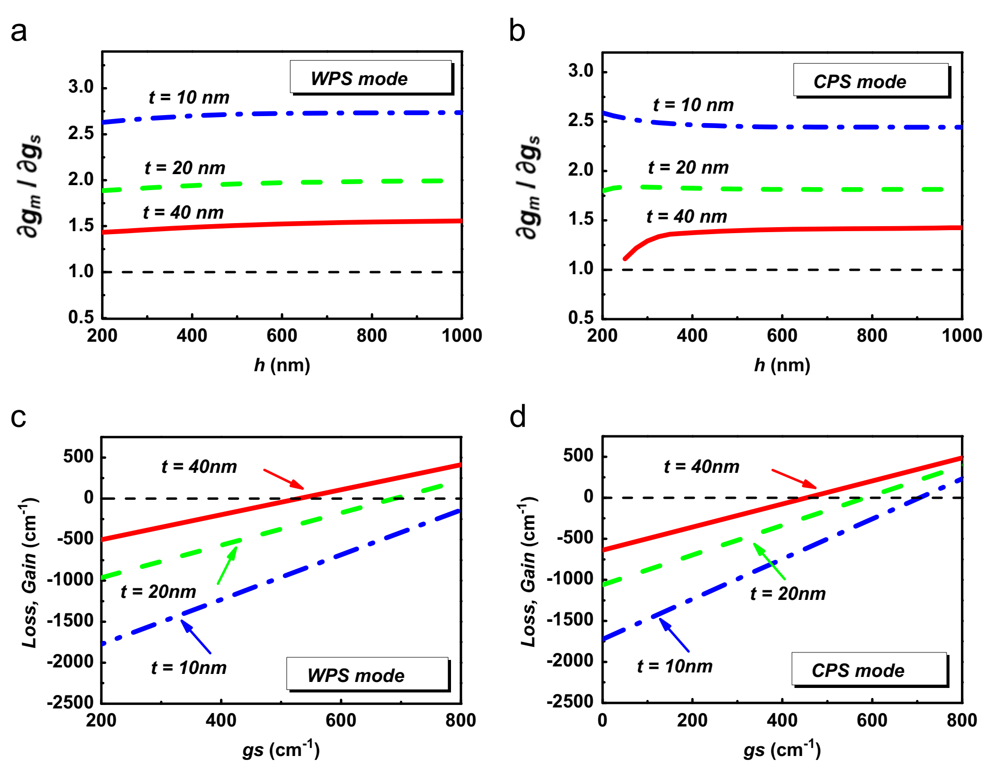

Fig. 6. (a,b) The gain enhancement ratios of $\partial g_m/\partial g_s$ for the WPS and CPS modes supported by various geometries. (c,d) The dependence of modal gain or loss of the two modes on the introduced gain coefficient of the material inside the slot region. The crossing points of the solid lines and the black dashed-lines in (c) and (d) correspond to the critical conditions for lossless propagation, where the imaginary part of the effective index for the plasmonic mode equals zero.

crossing points of the solid lines and the dashed-lines shown in Fig. 6(c) and (d). At these critical conditions, the imaginary part of the modal effective index equal zero, enabling lossless propagation of the mode at the subwavelength scale. Here, for the considered structures, a gain medium with coefficients around hundreds of cm^{-1} is sufficient to fully compensate the modal loss. Such a critical material gain for lossless mode propagation can be greatly reduced by further widening the slot region of the plasmonic waveguide. Along with the results shown in Figs. 3(c) and 4(c), it can be revealed that there is a tradeoff between the critical material gain coefficient and the mode confinement. A waveguide with a narrower slot requires a smaller critical material gain coefficient for lossless propagation, while demonstrating a larger mode area and weaker field confinement. On the other hand, for the structure with a wider slot region, its mode area can be much smaller than that of the narrow slot case despite of the relatively large critical material gain coefficient. Gain enhancement can be observed from Fig. 6(c) and (d) as the slopes of these lines exceed 1. It is also illustrated that waveguides with narrower slots usually correspond to larger slopes, indicating more significant gain enhancements achieved in these cases.

4. Conclusions

In summary, we have proposed and investigated a novel plasmonic waveguide that comprises a V-shaped dielectric slot sandwiched between a reverse metal wedge and a metallic groove substrate. Through incorporation of a gain material into the slot region, the propagation losses of the supported wedge plasmonic slot and channel plasmonic slot mode can be effectively compensated. It is revealed that due to the dramatic local field enhancements in the slot, giant gain enhancement is also observable. The proposed plasmonic slot structure can facilitate potential applications in compact active waveguides and components.

Acknowledgments

The work at Beihang University was supported by 973 Program (2009CB930701), NSFC (61221061/61077064), National Key Scientific Instruments and Equipment Development Special Fund Management (2011YQ0301240502) and Scholarship Award for Excellent Doctoral Student granted by Ministry of Education at Beihang University.

References

[1] W.L. Barnes, A. Dereux, T.W. Ebbesen, Nature 424 (2003) 824.
[2] D.K. Gramotnev, S.I. Bozhevolnyi, Nature Photonics 4 (2010) 83.
[3] G.S. Wiederhecker, C.M.B. Cordeiro, F. Couny, F. Benabid, S.A. Maier, J.C. Knight, C.H.B. Cruz, H.L. Fragnito, Nature Photonics 1 (2007) 115.
[4] M. Lipson, Journal of Lightwave Technology 23 (2005) 4222.
[5] J. Takahara, S. Yamagishi, H. Taki, A. Morimoto, T. Kobayashi, Optics Letters 22 (1997) 475.
[6] P. Berini, Physical Review B 61 (2000) 10484.
[7] D.F.P. Pile, T. Ogawa, D.K. Gramotnev, Y. Matsuzaki, K.C. Vernon, K. Yamaguchi, T. Okamoto, M. Haraguchi, M. Fukui, Applied Physics Letters 87 (2005) 261114.
[8] G. Veronis, S.H. Fan, Optics Letters 30 (2005) 3359.
[9] D.F.P. Pile, D.K. Gramotnev, Optics Letters 29 (2004) 1069.
[10] D.K. Gramotnev, D.F.P. Pile, Applied Physics Letters 85 (2004) 6323.
[11] S.I. Bozhevolnyi, V.S. Volkov, E. Devaux, T.W. Ebbesen, Physical Review Letters 95 (2005).
[12] S.I. Bozhevolnyi, V.S. Volkov, E. Devaux, J.Y. Laluet, T.W. Ebbesen, Nature 440 (2006) 508.
[13] S.I. Bozhevolnyi, Optics Express 14 (2006) 9467.
[14] M. Yan, M. Qiu, Journal of the Optical Society of America B 24 (2007) 2333.
[15] E. Moreno, F.J. Garcia-Vidal, S.G. Rodrigo, L. Martin-Moreno, S.I. Bozhevolnyi, Optics Letters 31 (2006) 3447.
[16] Y.S. Bian, Z. Zheng, X. Zhao, Y.L. Su, L. Liu, J.S. Liu, J.S. Zhu, T. Zhou, Highly confined hybrid plasmonic modes guided by nanowire-embedded-metal grooves for low-loss propagation at 1550 nm, IEEE Journal of Selected Topics in Quantum Electronics, http://dx.doi.org/10.1109/JSTQE.2012.2212002, in press.
[17] D.F.P. Pile, T. Ogawa, D.K. Gramotnev, T. Okamoto, M. Haraguchi, M. Fukui, S. Matsuo, Applied Physics Letters 87 (2005) 061106.
[18] E. Moreno, S.G. Rodrigo, S.I. Bozhevolnyi, L. Martin-Moreno, F.J. Garcia-Vidal, Physical Review Letters 100 (2008) 023901.
[19] A. Boltasseva, V.S. Volkov, R.B. Nielsen, E. Moreno, S.G. Rodrigo, S.I. Bozhevolnyi, Optics Express 16 (2008) 5252.
[20] Y.S. Bian, Z. Zheng, Y. Liu, J.S. Zhu, T. Zhou, Optics Express 19 (2011) 22417.
[21] V.S. Volkov, S.I. Bozhevolnyi, E. Devaux, J.Y. Laluet, T.W. Ebbesen, Nano Letters 7 (2007) 880.
[22] R.B. Nielsen, I. Fernandez-Cuesta, A. Boltasseva, V.S. Volkov, S.I. Bozhevolnyi, A. Klukowska, A. Kristensen, Optics Letters 33 (2008) 2800.
[23] K.C. Vernon, D.K. Gramotnev, D.F.P. Pile, Journal of Applied Physics 103 (2008).
[24] T. Srivastava, A. Kumar, Journal of Applied Physics 106 (2009) 043104.
[25] J. Dintinger, O.J.F. Martin, Optics Express 17 (2009) 2364.
[26] S. Lee, S. Kim, Optics Express 19 (2011) 9836.
[27] Y.S. Bian, Z. Zheng, X. Zhao, Y.L. Su, L. Liu, J.S. Liu, J.S. Zhu, T. Zhou, IEEE Photonics Technology Letters 24 (2012) 1279.
[28] R.F. Oulton, V.J. Sorger, D.A. Genov, D.F.P. Pile, X. Zhang, Nature Photonics 2 (2008) 496.
[29] J. Grandidier, G.C.D. Francs, S. Massenot, A. Bouhelier, L. Markey, J.C. Weeber, C. Finot, A. Dereux, Nano Letters 9 (2009) 2935.
[30] M.A. Noginov, G. Zhu, A.M. Belgrave, R. Bakker, V.M. Shalaev, E.E. Narimanov, S. Stout, E. Herz, T. Suteewong, U. Wiesner, Nature 460 (2009) 1110.
[31] M. Ambati, S.H. Nam, E. Ulin-Avila, D.A. Genov, G. Bartal, X. Zhang, Nano Letters 8 (2008) 3998.
[32] S.M. Garcia-Blanco, M. Pollnau, S.I. Bozhevolnyi, Optics Express 19 (2011) 25298.
[33] J.T. Robinson, K. Preston, O. Painter, M. Lipson, Optics Express 16 (2008) 16659.
[34] L.F. Gao, L.X. Tang, F.F. Hu, R.M. Guo, X.J. Wang, Z.P. Zhou, Optics Express 20 (2012) 11487.
[35] D.X. Dai, Y.C. Shi, S.L. He, L. Wosinski, L. Thylen, Optics Express 19 (2011) 12925.