Numerical Simulation and Analysis of Active Nanoplasmonic Waveguide

Qian Wang, Jing Pu and Seng-Tiong Ho

***Abstract*- Numerical simulation and analysis of an active nanoplasmonic waveguide with a semiconductor gain medium for light amplification is presented. This nanoplasmonic waveguide has a sub-wavelength light confinement (core cross-section is ~130 ×100 nm^2 in the numerical example) and a much higher modal gain and slope as compared to the conventional semiconductor waveguide, which makes it suitable for active nano-plasmonics devices and nanophotonic circuitry applications.**

***Index Terms*-active plasmonic waveguide, FDTD, modal analysis, modal gain**

I. INTRODUCTION

Active plasmonic waveguide combining gain medium can not only overcome the metal loss but also amplify the light to construct active plasmonic devices, e.g., nano-lasers. Various active plasmonic waveguide structures are proposed recently and examples include a thin-film metal strip on a semiconductor substrate, a metal strip sandwiched between two semiconductor active regions, or a semiconductor strip on metal surface, etc [1-6]. Different from these existing structures, the active plasmonic waveguide considered in this paper has a structure of metal/ p-cladding/active region/metal on an n-type substrate in the vertical direction as shown in Fig.1. The lateral light confinement of this nanoplasmonic waveguide is based on the high-index contrast, but it can have much smaller core width as shown later in paper.

To investigate the modal gain of this active plasmonic waveguide, a numerical comparison study between a conventional semiconductor waveguide and this plasmonic waveguide is carried out using an active finite-difference-time-domain simulation combining gain medium modeling and Drude modeling for the metal. The numerical example shows that the plasmonic waveguide requires a higher transparent current threshold to compensate the metal loss but has an enhanced modal gain (a higher modal gain and gain slope) as compared to the semiconductor waveguide, which is because of the improved light confinement in the active region and a larger group refractive index.

For the channel nanoplasmonic waveguide, the influence of width on the light confinement and modal gain is investigated using modal analysis. Simulation results indicated that the vertical plasmon confinement enhances the light confinement in the horizontal direction. The numerical example shows a waveguide cross-section of ~130 ×100 nm^2, which is the smallest active plasmonic waveguide reported to the best of our knowledge and this active plasmonic waveguide has an higher modal gain as compared to the semiconductor planar waveguide. This sub-wavelength light confinement and enhanced modal gain makes it to be a useful building block for various active nanoplasmonics devices and nanophotonic circuitry.

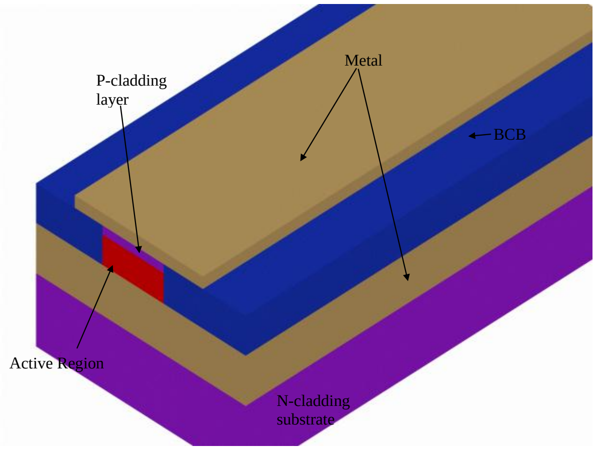


Fig.1 Active plasmonic waveguide considered in this letter, which consists of a metal layer, a thin p-cladding layer, active region and metal layer on the n-cladding substrate

II. MODAL GAIN OF NANOPLASMONIC WAVEGUIDE WITH FDTD SIMULATION

We started from a comparison study of modal gain between the plasmonic waveguide and a conventional semiconductor waveguide, which consists of a p-cladding, n-cladding, and core sandwiching an active region. This active semiconductor waveguide operates at the optical communication wavelength window (~1550nm) and transverse electric (TE) mode (electric field is parallel to the wafer substrate). The thickness of the core is 500 nm and the active region has a thickness of 100 nm as the numerical example. For the active nanoplasmonic waveguide, the active region is also chosen to be 100 nm for the numerical example. The p-layer has a same thickness of 30 nm as in Ref.[7]. The metal considered in this letter is silver, of which the dielectric constant is defined with the Drude modal, where $\omega_p = 1.39\times10^{16}$, $\gamma_m = 3.2258\times10^{13}$, $\varepsilon_\infty = 3.7$ and ω is the angular frequency of propagating light.

FDTD simulation combining the multi-level and multi-electron model for the gain medium [8] and Drude modal for the silver is used to study the modal gain of this

Manuscript received May.18, 2012.

Q. Wang and J. Pu with Data Storage Institute, Agency for Science, Technology and Research (wang_qian@dsi.a-star.edu.sg, Pu_jing@dsi.a-star.edu.sg).

S. Ho is with Dept. Electrical Engineering and Computer Science, Northwestern University, Evanston, IL, 60208 (stho@northwestern.edu).

nanoplasmonic waveguide.

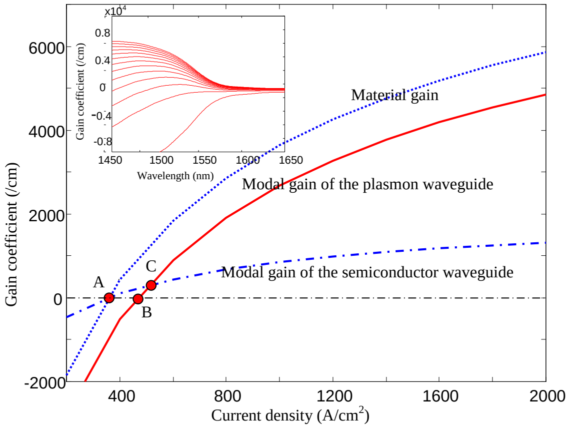


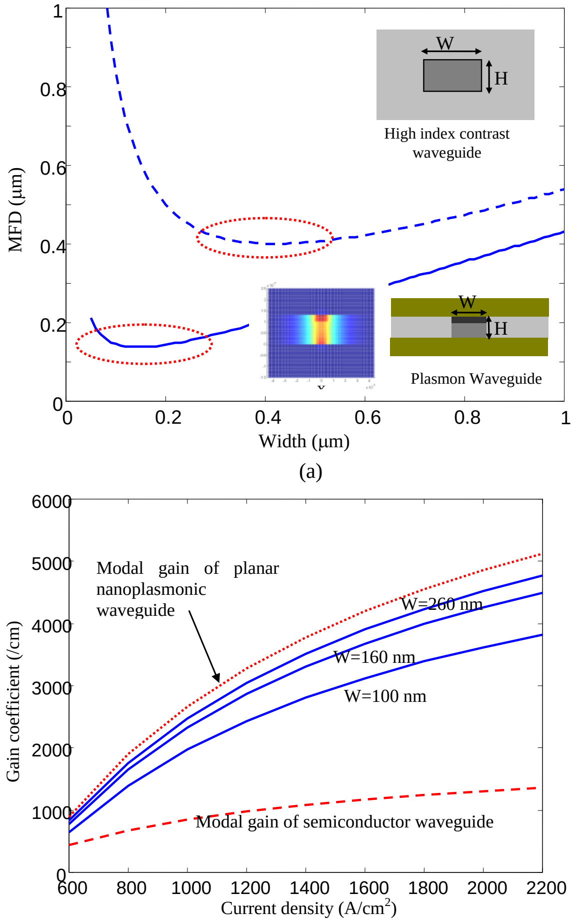
Fig.2 Gain coefficient at wavelength 1500 nm under different injection current densities for the material gain, modal gain of the Plasmon waveguide and modal gain of the semiconductor waveguide; inset is the gain spectra of the plasmonic waveguide.

The gain spectra are calculated through simulating the propagation of a pulse along the waveguide after the medium is pumped to a steady state with a given injection current density. The inset of Fig.2 gives the gain spectra of a plasmonic waveguide under different pumping conditions. The gain coefficient at wavelength 1500 nm for the material gain, plasmonic waveguide and semiconductor waveguide under different injection current densities in Fig.2 shows that the nanoplasmonic waveguide has a much higher modal gain/slope modal gain as compared to the semiconductor waveguide, which reveals that the gain medium can not compensate the metal loss but also the plasmonic waveguide has an enhanced modal gain due to the higher light confinement and larger group refractive index as compared to the semiconductor waveguide.

For the channel plasmonic waveguide, the active region and top p-cladding are etched to form the core of the waveguide for the lateral light confinement. After using the effective index method, the mode-field-diameter (MFD) of the waveguide is calculated and it is shown in Fig.3a that the plasmonic waveguide can have a much smaller waveguide width (down to 100 nm) as compared to the dielectric waveguide (~400 nm). The eigenmode field profile of the nanoplasmonic waveguide is shown in the inset of Fig.3 when the waveguide cross-section is 130×100 nm^2. With full-vectorial eigenmode analysis, the modal gain for this nanoplasmonic waveguide is calculated for a width of 100 nm, 160 nm and 260 nm. Numerical results in Fig.3b shows the modal gain of this nanoplasmonic waveguide can have a higher modal gain compared to the semiconductor waveguide.

III. CONCLUSION

An active nanoplasmonic waveguide with a semiconductor gain medium for light amplification has been investigated numerically. The numerical study shows this planar plasmonic waveguide structure can have a higher modal gain/slope as compared to the conventional semiconductor waveguide. The plasmon mode confinement in the vertical direction enhances the light confinement in the horizontal direction and the numerical example shows a cross-section of ~130 ×100 nm^2, which is the smallest active plasmonic waveguide reported to the best of the knowledge. This nanoplasmonic waveguide can be a useful building block for various active nanoplasmonics devices and nanophotonic circuitry.



(a)

(b)

Fig.3 a) mode-field-diameter in x-direction for dielectric waveguide and plasmonic waveguide; inset are the eigenmode field profile and waveguide cross-sections; b) Gain coefficient of the plasmonic waveguide when width is 100 nm, 160 nm and 260 nm.

REFERENCE

[1] D. A. Genov, M. Ambati and X. Zhang, IEEE J. Quantum Electronics, Vol.43, No.11, pp.1104-1108, 2007.

[2] J. Grandidier, G. Francs, S. Massenot, A. Bouhelier, L. Markey, J. Weeber, C. Finot, and A. Dereux, Nano Letters, Vol.9, No.8, pp. 2935-2939, 2009.

[3] M. P. Nezhad, K. Tetz, and Y. Fainman, Vol.12, No.17, pp. 4072-4078, 2004.

[4] A. M. Lakhani, M. Kim, E. K. Lau and M. Wu, Optics Express, Vol. 19, No.19, pp. 18237-18245, 2011.

[5] M. Z. Alam, J. Meier, J. S. Aitchison and M. Mojahedi, Optics Express, Vol.15, No.1, pp. 176-182, 2006.

[6] R. A. Flynn, C. S. Kim, I. Vurgaftman, M. Kim, J. R. Meyer, A. J. Makinen, K. Bussmann, L. Cheng, F.-S. Choa, and J. P. Long, Vol.19, No.9, pp.8954-8961, 2011.

[7] C. Manolatou and F. Rana, IEEE J. Quantum Electronics, Vol.44, No.5, pp.435-447, 2008.

[8] Y. Huang and S. T. Ho, Opt. Expr., Vol.14, No.8, pp.3569-3587, 2006.