Theoretical study of loss compensation in long-range dielectric loaded surface plasmon polariton waveguides

Sonia M. García-Blanco[1], Markus Pollnau[1] and Sergey I. Bozhevolnyi[2]
[1]*Integrated Optical MicroSystems Group, MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217,7500 AE Enschede, The Netherlands*
s.garciablanco@utwente.nl
[2]*Institute of Technology and Innovation,*
University of Southern Denmark, DK-5230 Odense, Denmark

ABSTRACT
In this paper, a theoretical study of loss compensation in long-range dielectric loaded surface plasmon waveguides (LR-DLSPPs) is presented. Although extendable to other gain materials, rare-earth doped double tungstates are used as gain material in this work. Two different structures are studied and the effect of the different waveguide geometrical parameters on the material gain required to fully compensate the propagation losses are reported. The simulations were performed at 1.55 µm wavelength. A material gain as low as 12.5 dB/cm was determined as sufficient to obtain complete loss compensation in one of the proposed waveguide structures supporting sub-micron lateral mode dimension.

Keywords: plasmonic waveguides; gain material; rare-earth ions; double tungstates.

1. INTRODUCTION

Surface plasmon polaritons (SPPs), evanescent electromagnetic waves propagating along metal-dielectric interfaces, have been the subject of numerous studies due to their unique properties. Promising applications in a variety of fields include optical biosensing, data storage, photovoltaic cells, and highly integrated photonic circuits [1]-[3]. Many different plasmonic waveguiding configurations have been proposed and demonstrated over the past few years [4]-[9]. In general, SPP waveguides are subject to a trade-off between mode-field confinement and propagation loss, exhibiting either good optical confinement but short propagation distances [6], or long propagation distances necessitating large mode profiles [7]. Recently, a novel type of plasmonic waveguide configuration was proposed, long-range dielectric-loaded surface plasmon polariton (LR-DLSPP) waveguides that combine the millimeter-range propagation with a relatively strong mode confinement [8], [9]. Reduced propagation losses provided by this novel structure permit enlarging the range of gain materials that can be selected for loss compensation.

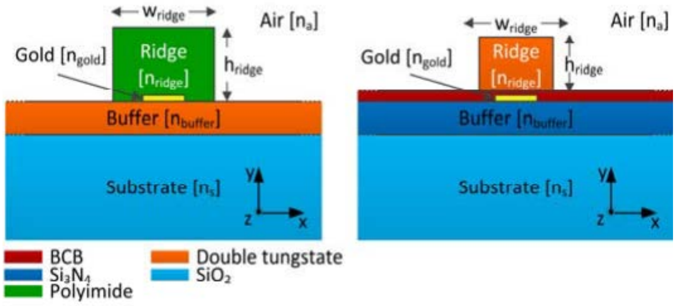
Many efforts have been directed towards compensating propagation losses in plasmonic waveguides by use of different gain materials [10]-[13]. In this work, we proposed the use of rare-earth (RE) doped double tungstates, which have been recently reported to provide elevated gain [14] with very interesting characteristics, such as amplification without distortion of very-high-rate signals in the small-signal-gain regime and large gain bandwidth up to a few tens of nanometers, interesting for broadband optical amplification and the generation of ultra-short laser pulses.

In this work, loss compensation in LR-DLSPP waveguides by optical gain provided by a RE-doped double tungstate material incorporated into the LR-DLSPP configuration is theoretically studied. Two structures are presented. The effect of different waveguide parameters on the efficiency of the material gain to compensate propagation losses is evaluated. Lossless propagation is predicted for material gain as low as 12.5 dB/cm, with a mode size comparable to conventional dielectric-loaded surface plasmon polariton waveguides [15].

2. DESCRIPTION OF THE PROPOSED STRUCTURES

The generic LR-DLSPP structure includes a low-refractive-index substrate material, a buffer layer of a high-refractive-index material, a metal stripe and a dielectric ridge, the dimensions and refractive index of which should be chosen to balance the electric fields at both sizes of the gold stripe to ensure long-range propagation [8]-[9].

In this study, the substrate material chosen is SiO_2 (n ~ 1.46) and the metal selected is gold (n_{gold} = 0.55+j11.5 [16]). The wavelength utilized is 1.55 μm. The dimensions of the gold stripe were fixed in all cases to a thickness of 15 nm and a width of 200 nm. The gain material utilized is RE-doped double tungstate with refractive index ~2.05. In Structure 1 the gain material is added as the buffer layer while the ridge is made of polyimide (n ~ 1.9). In Structure 2, the buffer layer chosen is Si_3N_4 (n_{Si3N4} ~2.05) and the gain is added to the ridge. A 100 nm-thin BCB adhesive layer is introduced between the buffer layer and the ridge as part of the integration procedure of the gain material to the structure. Figure 1 shows the two structures under study.



(a) *(b)*

Figure 1.Proposed LR-DLSPP structures: (a) Gain material as the bufferlayer; (b) Gain material as the ridge.

3. FINITE DIFFERENCE CALCULATIONS

Finite difference (FD) calculations with perfect magnetic conductor (PMC) and perfectly matched layers (PML) were carried out using the PhoeniX B.V. The size of the calculation window was chosen as 20 μm by 20 μm to ensure that the field at the boundaries of the window was zero. Since the simulated structures present regions with different sizes, these thinner structures were artificially divided in the required number of sublayers to ensure that enough grid points were assigned to these critical areas. The number of sublayers was selected so that the addition of more layers only produced negligible variation in the results. Figure 2 shows the mesh utilized in the simulations for Structure 2. In the metal, a grid size of 0.75 nm was utilized (i.e., the metal stripe of 15 nm thickness was represented by 20 sublayers).

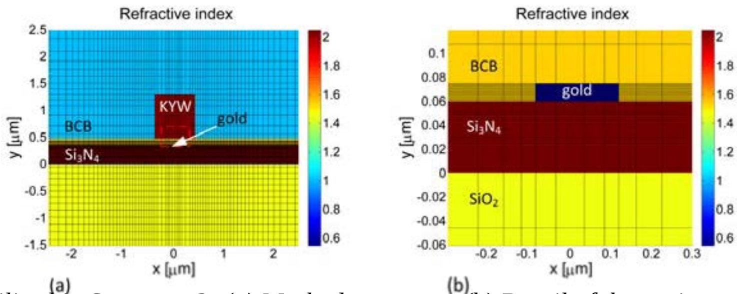


Figure 2. Mesh utilized in Structure 2: (a) Meshed structure; (b) Detail of the region around the gold layer.

4. RESULTS

The two structures proposed in Section 2 were simulated as described in Section 3. The net propagation loss of the structures was calculated as a function of the buffer thickness for different ridge dimensions. It is well known that in a LR-DLSPP waveguide, the electric fields above and below the gold stripe should be as balanced as possible in order to minimize propagation losses [8]. Furthermore, in order to enhance the effectiveness of loss compensation by the gain material, the confinement of the mode into the gain region should be maximized. Both effects can be related as

$$\alpha_{net} = \alpha_{loss} - \Gamma g_{mat} \quad (1)$$

where α_{net} is the net modal loss in dB/cm, α_{loss} is the propagation loss of the passive structure in dB/cm, Γ is the fraction of optical power overlapping with the gain region, and g_{mat} is the material gain provided by the material utilized in the gain region. α_{loss} finds a minimum at the point of electric field balance. Figure 3 (a) shows this effect applied to Structure 1. For each ridge size, there is a thickness of the buffer layer that minimizes the losses. In the case of Structure 1, as the ridge height is increased for a given ridge width, a thicker buffer is required to balance the electric field above and below the gold stripe. The power confinement to the active gain region (Figure 3 (e)), which in this case is the buffer layer, follows the opposite trend. The thinner the ridge, the more the mode is pushed towards the active buffer layer. Figures 3 (b)-(d) shows the combined effect for different values of the material gain of the buffer layer. Figure 3 (f) shows the evolution of the lateral mode dimension as a function of buffer thickness for different ridge dimensions.

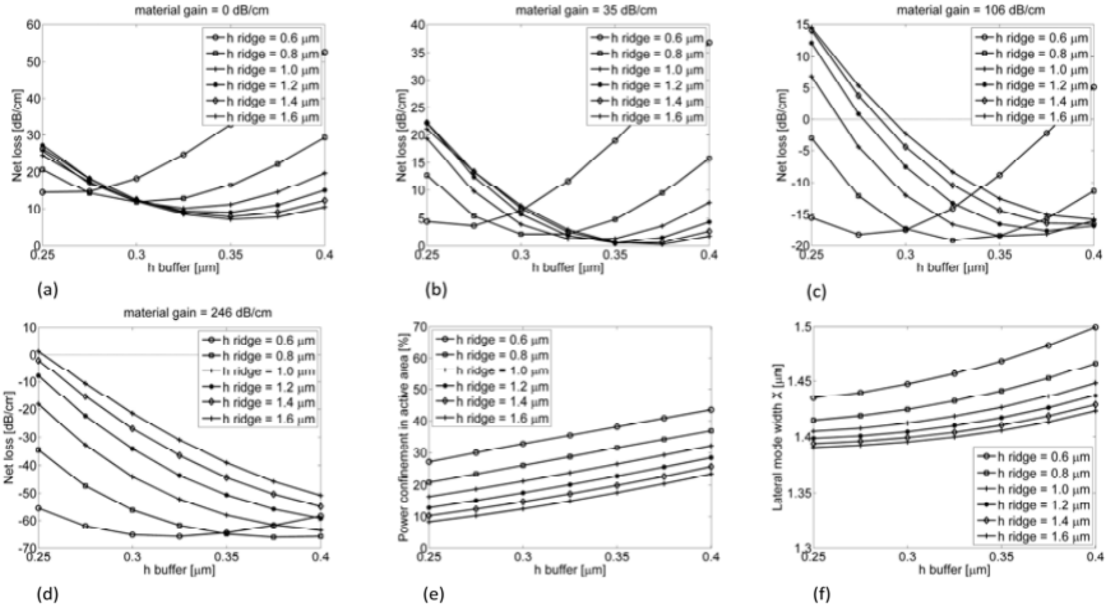


Figure 3. Effect of different geometrical parameters on the performance of Structure 1: (a)-(e) Net loss versus buffer thickness for a ridge width of 1.6 μm and different ridge heights. Material gain investigated are 0, 35, 106 and 246 dB/cm; (e) Power confinement in active area; (f) Lateral mode width.

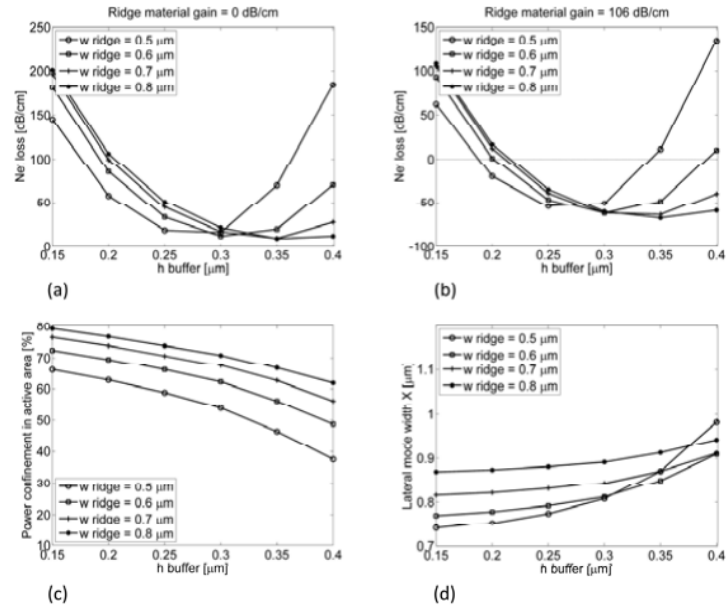


Figure 4. (a) Net loss for Structure 2 with no gain, ridge height of 0.8 μm and several ridge widths; (b) Net loss when using material gain of 106 dB/cm; (d) Power confinement in active area; (d) Lateral mode width.

Similar set of simulations were carried out for Structure 2 (Figure 4). The much larger confinement to the active region, in this case the waveguide ridge, permits a much more efficient utilization of the material gain for plasmonic loss compensation. Figure 5 shows the mode profiles of the waveguide geometries requiring the smallest material gain to achieve full loss compensation. A minimum material gain of 37 dB/cm is required for Structure 1 (ridge dimensions 1.6x1.6 μm^2 and buffer thickness 0.37 μm). A gain as small as 12.5 dB/cm suffice to fully compensate propagation losses in Structure 2 (ridge dimensions 0.8x0.8 μm^2 and buffer thickness 0.35 μm). This latter structure supports a propagation mode with sub-micron lateral dimension (0.92 μm).

5. CONCLUSIONS

The structures considered in this paper show a great potential to reach the goal of loss compensation in plasmonic waveguides and are promising for plasmon amplification and lasing. The low material gain required to compensate propagation losses, 37 dB/cm in Structure 1 and 12.5 dB/cm in Structure 2 broadens the range of gain materials that can be utilized. RE-doped double tungstate gain materials were selected in this study due to their very good match of refractive index with the materials utilized in the structure and the interesting characteristics of the gain they can provide. Experimental demonstration of the considered structures will constitute the next milestone on the way towards lossless plasmonic waveguides.

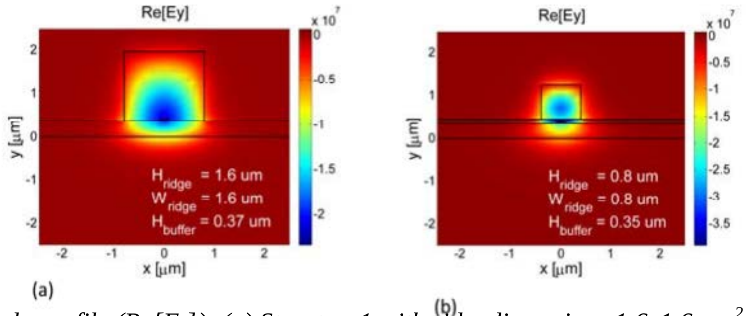


Figure 5.2-D mode profile (Re[E_y]): (a) Structure1 with ridgedimensions 1.6x1.6 µm^{2}and buffer height of 0.37 µm;(b)Structure2 with ridge dimensions 0.8x0.8 µm^{2}and buffer height of 0.35 µm.

ACKNOWLEDGEMENTS

The authors acknowledge support from the COST Action MP0702: Towards functional sub-wavelength photonic structures. Support from the FP7 Marie Curie Career Integration Grant PCIG09-GA-2011-29389 (SMGB) and. Danish Council for Independent Research FTP-project No. 09-072949 ANAP (SIB) is also appreciated.

REFERENCES

[1] Q. Min, C. Chen, P. Berini, and R. Gordon, “Long range surface plasmons on asymmetric suspended thin film structures for biosensing applications,” Opt. Express **18**, 19009-19019 (2010).

[2] M. Mansuripur, A. R. Zakharian, A. Lesuffleur, S.-H. Oh, R. J. Jones, N. C. Lindquist, H. Im, A. Kobyakov, and J. V. Moloney, “Plasmonic nano-structures for optical data storage,” Opt. Express **17**, 14001-14014 (2009).

[3] H. A. Atwater and A. Polman, “Plasmonics for improved photovoltaic devices,” Nat. Mater. **9**, 205-213 (2010).

[4] R. F. Oulton, V. J. Sorger, D. A. Genov, D. F. P. Pile, and X. Zhang, “A hybrid plasmonic waveguide for subwavelength confinement and long-range propagation,” Nat. Photonics **2**, 496-500 (2008).

[5] J. A. Dionne, L. A. Sweatlock, H. A. Atwater, and A. Polman, “Plasmon slot waveguides: Towards chip-scale propagation with subwavelength-scale localization,” Phys. Rev. B **73**, 035407 (2006).

[6] T. Holmgaard and S. I. Bozhevolnyi, “Theoretical analysis of dielectric-loaded surface plasmon-polariton waveguides,” Phys. Rev. B **75**, 245405 (2007).

[7] P. Berini, “Plasmon-polariton waves guided by thin lossy metal films of finite width: Bound modes of symmetric structures,” Phys. Rev. B **61**, 10484-10503 (2000).

[8] T. Holmgaard, J. Gosciniak, and S. I. Bozhevolnyi, “Long-range dielectric-loaded surface plasmon polariton waveguides,” Opt. Express **18**, 23009-23015 (2010).

[9] J. Gosciniak, T. Holmgaard, and S. I. Bozhevolnyi, “Theoretical analysis of long-range dielectric-loaded surface plasmon polariton waveguides,” J. Lightwave Technol. **29**, 1473-1481 (2011).

[10] J. Grandinier, G. Colas des Francs, S. Massenot, A. Bouhelier, L. Markey, J.-C. Weeber, C. Finot, and A. Dereux, “Gain-assisted propagation in a plasmonic waveguide at telecom wavelength,” Nano Lett. **9**, 2935-
2939 (2009).

[11] I. De Leon and P. Berini, “Amplification of long-range surface plasmons by a dipolar gain medium,” Nat. Photonics **4**, 382-387 (2010).

[12] A. V. Krasavin, T. P. Vo, W. Dickson, P. M. Bolger, and A. V. Zayats, “All-plasmonic modulation via stimulated emission of copropagating surface plasmon polaritons on a substrate with gain,” Nano Lett. **11**, 2231-2235 (2011).

[13] I. P. Radko, M. G. Nielsen, O. Albrektsen, and S. I. Bozhevolnyi, “Stimulated emission of surface plasmon polaritons by lead-sulphide quantum dots at near infra-red wavelengths,” Opt. Express **18**, 18633-18641 (2010).

[14] D. Geskus, S. Aravazhi, S. M. García-Blanco, and M. Pollnau, “Giant optical gain in a rare-earth-ion-doped microstructure,” Adv. Mater., in press (2011).

[15] S. M. García-Blanco, M. Pollnau, and S. I. Bozhevolnyi, “Loss compensation in long-range dielectric-loaded surface plasmon-polariton waveguides”, Opt. Express **19**, 25298-25311 (2011).

[16] M. L. Theye, “Investigation of the optical properties of Au by means of thin semitransparent films,” Phys. Rev. B **2**, 3060-3078(1970).