Gap Surface Plasmon Waveguide Analysis

Michael G. Nielsen
Institute of Technology and Innovation (ITI),
University of Southern Denmark,
DK-5230 Odense M, Denmark
Email: mgni@iti.sdu.dk

Sergey I. Bozhevolnyi
Institute of Technology and Innovation (ITI),
University of Southern Denmark,
DK-5230 Odense M, Denmark
Email: seib@iti.sdu.dk

***Abstract*—Plasmonic waveguides supporting gap surface plasmons (GSPs) localized in a dielectric spacer between metal films are investigated numerically and the waveguiding properties at telecommunication wavelengths are presented. Especially, we emphasize that the mode confinement can advantageously be controlled by the waveguide width and the dielectric spacer thickness and thus allows for straightforward fabrication of highly integrated waveguides by a single lithography step.**

I. Introduction

Metal-based waveguides supporting surface plasmon polariton modes [1] have received much attention in recent years due to the possibility of subwavelength mode localization [2], which allows for a broad range of applications such as highly integrated waveguide components [3], [4], [5] and for efficient coupling of freely propagating waves to nano-sized emitters such as quantum dots, nitrogen-vacancy centres in nanodiamonds [6], and single molecules. In this respect, GSP waveguides deserve a careful study since they support highly localized plasmonic modes without cutoff and maximize the mode field intensity in a dielectric gap which can advantageously be doped in order to compensate for loss due to absorption in metal or function as a nonlinear media with the purpose of phase-modulating a transmitted signal via the linear electro-optic effect.

In this report, we present the waveguiding properties at telecommunication wavelengths in terms of effective mode index, propagation length, and coupling length of GSP waveguide configurations amenable for fabrication where the gap size can be controlled simply by e.g. spin-coating or physical vapor deposition. All the numerical results are obtained with the commercial software COMSOL Multiphysics.

II. Results

GSP-modes are formed in dielectric gaps between metals as a consequence of coupling between individual metal-dielectric interface SPP-modes [8]. Truncating only the top metal layer [Fig. 1 (a)] or both top metal layer and the dielectric [Fig. 1 (b)], allows for mode localization not only in the transverse direction by control of the dielectric thickness, t, but also in the lateral direction by the waveguide width, w. This can be verified by numerically assessing the real part of effective mode index, $\mathrm{Re}\{\mathrm{n}_{\mathrm{eff}}\}$ [Fig. 2 (a)], and propagation length $L_p = 1/[2\mathrm{Im}\{\mathrm{n}_{\mathrm{eff}}\}/k_0]$ [Fig. 2 (b)] as a function of width, w, when the dielectric spacer thickness is fixed to $t = 150nm$. An interesting feature for both configurations is that while the first order mode is cutoff when w decreases, the fundamental mode does not exhibit cutoff as seen by the increase in the fundamental mode effective index. Distributions of the electric-field magnitude for the fundamental mode when $w = 700nm$ [Fig. 3 (a,d)] show that the mode energy is localized and quite homogeneously distributed underneath the strip in the dielectric, but when $w = 30nm$, the mode energy is rather

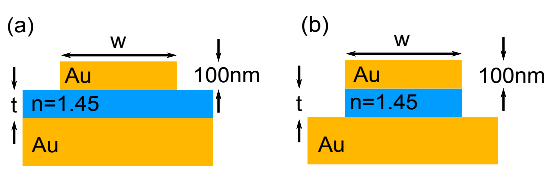

Fig. 1. Cross sections of two GSP waveguide configurations with (a) continuous and (b) truncated dielectric spacers having refractive index $n = 1.45$ placed between a gold substrate and a gold stripe. Gold permittivity is obtained from [7].

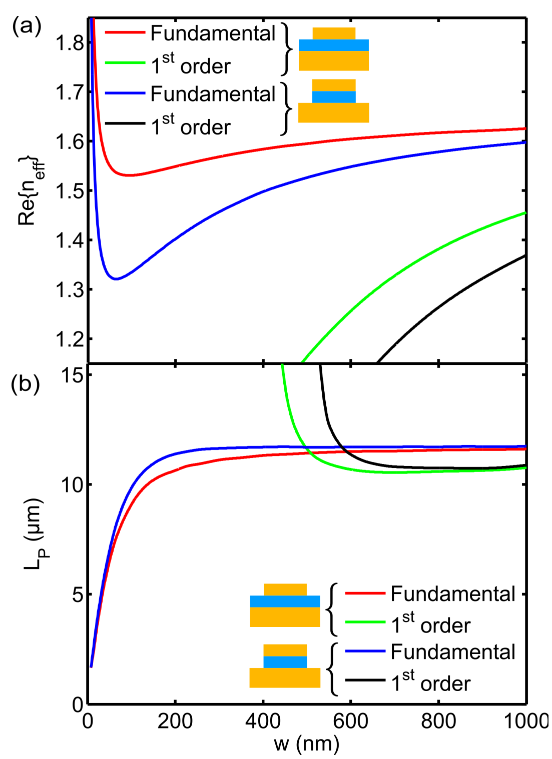

Fig. 2. (a) Real part of effective mode index, $\mathrm{Re}\{\mathrm{n}_{\mathrm{eff}}\}$, and (b) propagation length, L_p, for the fundamental and first order modes of two different GSP-waveguide configurations as a function of width, w, when the dielectric spacer is $t = 150nm$ and vacuum wavelength $\lambda_0 = 1.55\mu m$.

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localized in the vicinity of the strip [Fig. 3 (c,f)] because the GSP-mode upon decreasing width changes into a strip mode [9]. I.e. by tapering the GSP waveguide so that variations in the GSP wave vector are small on the scale of the GSP wavelength the fundamental mode can be nanofocused to a deep subwavelength volume with huge field enhancement [10].

Due to the inevitable Ohmic losses related to field penetration into the gold, the GSP waveguide propagation length L_p is limited to approximately $10\mu m$ when $t = 150nm$ and $w \geq 200nm$ [Fig. 2 (b)]. Though this is an order of magnitude larger than the plasmon wavelength and should allow for realization of integrated components, it will here be a great advantage to dope the dielectric with gain material which upon optical pumping partially compensates for Ohmic losses in the gold. Also, because of the usual trade-off between mode confinement and propagation length, the absorption losses can be reduced simply by tolerating a thicker dielectric so that the GSP mode becomes more delocalized in the dielectric and hence less confined. For example, when $t = 800nm$ the propagation length is $L_p \sim 40\mu m$ when $w \geq 600nm$, i.e. several tens of GSP wavelengths. We finally note, that GSP waveguides with $t = 150nm$ and a small separation gap of $\sim 100nm$ exhibit a coupling length of $17\mu m$, which is larger than the propagation length and thus ensures negligible cross talk between densely fabricated waveguides.

III. Conclusion

In summary, we have analyzed the waveguiding properties of GSP waveguides at telecommunication wavelengths including dependence of effective mode index and propagation length on the gap thickness, t, and waveguide width, w, showing that GSP waveguides are interesting w.r.t. nanofocusing and concentration of electromagnetic fields. By optimizing the waveguide parameters, the mode energy can be highly localized in the dielectric gap which is promising for efficient interaction with nano-sized emitters and may have applications in quantum optics and efficient loss compensation of guided plasmonic modes.

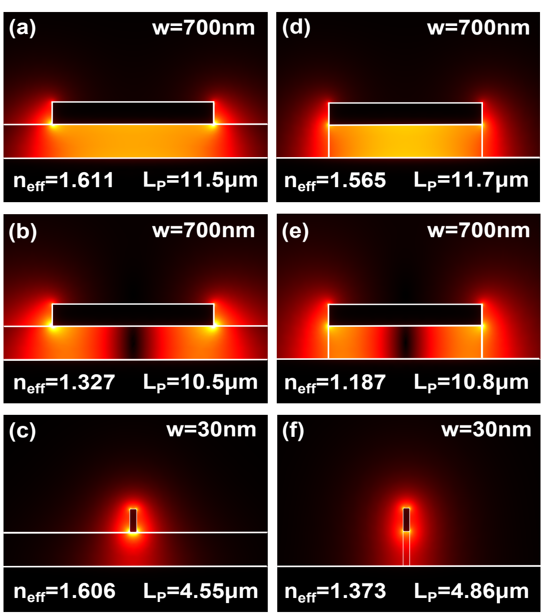

Fig. 3. Electric field magnitude for the two GSP waveguide configurations shown in Fig. 1 (a,b). (a,d) Fundamental mode, (b,e) first order mode and (c,f) strip mode.

Acknowledgment

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