Concept of Plasmonic Waveguide Inspired by Half-Mode Substrate-Integrated Waveguide

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***Abstract*— A new concept of a plasmonic waveguide for optical frequencies is introduced. The waveguide is inspired by the half-mode substrate-integrated waveguide (HMSIW), which is in use in the microwave regime. The design of the plasmonic HMSIW however requires to take into account the particularities of the materials in the optical regime, which leads to modified design rules compared to microwave frequencies. It is shown that the proposed nanoscale plasmonic HMSIW is able to guide electromagnetic waves over a short distance while being characterized by very compact size. The design parameters found in this paper are derived from electromagnetic simulations based on the Finite-Volume Time-Domain (FVTD) method.**

***Index Terms*— Plasmonics, SPP, HMSIW, FVTD.**

I. Introduction

Guiding electromagnetic waves at optical frequencies in the nanoscale regime is a challenging task because of the diffraction limit. However, in order to build nanoscale-optical waveguides, this limit can be circumvented by employing surface plasmon polaritons (SPPs) that can be excited at an interface between dielectrics and metals [1]. Metals, such as gold or silver, can support SPPs at optical frequencies owing to their appropriate complex permittivity, i.e. a negative real part and a small absolute imaginary part. These SPPs can be exploited to guide waves along dielectric-metal interfaces, taking advantage of the subwavelength confinement of electromagnetic waves [2].

In this paper, a new concept of an optical plasmonic waveguide is introduced. This concept is inspired by the half-mode substrate integrated waveguide (HMSIW) [3], which is scaled and adapted to be manufacturable and operable at optical frequencies. This plasmonic HMSIW is very compact as its width extends only over a small fraction of the excitation wavelength while it is able to guide electromagnetic waves over a distance equivalent to a few wavelengths. At this early stage, the basic operation of the waveguide is investigated through an analysis of its propagation constant, realized using 3D full-wave electromagnetic simulations. This is especially challenging because of the dispersive nature of metal at optical frequencies and because of the thin dielectric layer, sandwiched in between thicker gold layers. The vicinity of the dielectric-gold interface in the guide requires a very fine discretization in order to capture the propagating mode. Such a structure can be efficiently modeled with an unstructured grid, where the size of the elements can quickly grow within a few grid layers. A method which has been shown to successfully model plasmonic structures is the Finite-Volume Time-Domain (FVTD) method [4], [5].

After a brief introduction of the FVTD method, the basic design of the plasmonic HMSIW is presented. Principle design rules for an optimal operation of the waveguide are deduced from its FVTD analysis, and the difference to the microwave version are highlighted.

II. Simulation method: FVTD

Since the end of the 1980s, the FVTD method is successfully applied in computational electromagnetics. The method is especially well suited for multi-scale problems. Its explicit time-stepping scheme results in linear memory growth and at the same time the application in an unstructured, tetrahedral mesh provides the means to minimize the overall number of elements required for discretizing multi-scale problems. Additionally, a geometry-matched local-time stepping scheme provides a further reduction of the CPU time, commonly around a factor of 3 to 5 [6]. For long structures, such as waveguides, a conformal PML facilitates the size minimization of the computational domain while keeping the unintended reflections from the boundary at the same level as spherical PMLs [7].

III. Design of plasmonic HMSIW

The concept of a substrate-integrated waveguide (SIW) surfaced in 2001 in order to simplify the transition from a microstrip line to a rectangular waveguide [8]. Traditionally, the SIW side walls are realized as a row of vias. Five years later, a further size reduction was achieved with the half-mode substrate integrated waveguide (HMSIW) [9], [3]. In this paper, the concept of a HMSIW is scaled and adapted to optical frequencies resulting in the design of a compact nanoscale waveguide. The principle design of this plasmonic HMSIW is shown in Fig. 1. Its dimensions and materials are consistent with standard capabilities of modern nano-fabrication techniques. Similarly to the conventional HMSIW, a layer of conductor (gold [10]) is partly surrounding a very thin dielectric SiO_2 ($\varepsilon_r = 2.31$) layer. This constitutes one half of a rectangular waveguide

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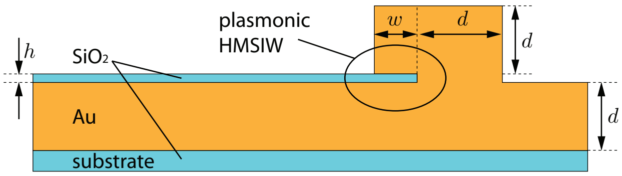

Fig. 1. Profile and dimensions of the plasmonic waveguide.

with height h and width w, where a half quasi-TE_{10} mode can propagate. As an important difference to a scaled microwave counterpart, the optical electromagnetic field is penetrating significantly into the gold because of a small negative permittivity. Therefore, the waveguide walls have to have a certain thickness in order to permit the plasmonic mode to build and propagate. Here the thickness is chosen as $d = 40\,\text{nm}$. The plasmonic HMSIW is modeled in

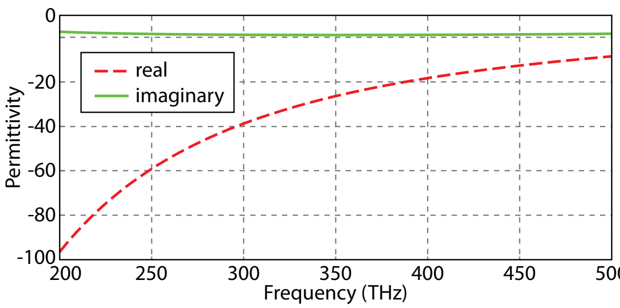

Fig. 2. Complex permittivity of gold in between 200 and 500 THz [4].

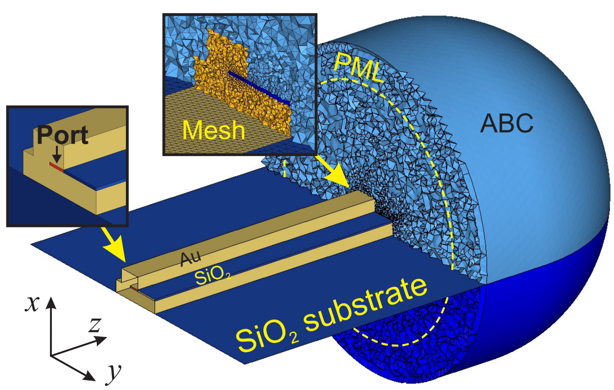

Fig. 3. Open view of the FVTD model of the plasmonic HMSIW. The insets show the port and the fine mesh employed at the waveguide region.

FVTD according to the geometry described above, with waveguide height $h = 5\,\text{nm}$, various widths in between $w = 10 \ldots 80\,\text{nm}$, and with a length of $L = 1.5\,\mu\text{m}$. The dispersive characteristic of gold, as plotted in Fig. 2, is approximated with a double-Lorentz single-Drude pole model, with parameters as in [4]. In order to capture the plasmonic effects of the waveguide, the SiO_2 inside the waveguide and the surrounding gold layer are discretized with a maximal linear cell size of 2 nm. This set-up results in a total of 4 to 7 million tetrahedral cells. An open view of the FVTD model is shown in Fig. 3. In the FVTD simulation, the mode in the guide is excited as half the TE_{10} mode of a perfect rectangular waveguide. A conformal PML boundary condition is applied on the cylindrical outer computational boundary.

IV. Results

The propagation constant $\gamma = \alpha + j\beta$ is determined from the FVTD simulations. The phase constant β is evaluated based on the guided wavelength λ_g which is measured by the average distance between two maxima of the propagating wave inside the waveguide. The attenuation constant α is determined by considering two points at distance z_1 and z_2 from the source in the guide

$$\alpha = (z_2 - z_1)^{-1} \cdot \ln |E_x(z_1)/E_x(z_2)| \,. \qquad (1)$$

For the analysis points z_1 and z_2 are chosen at a distance from the waveguide ends to avoid any detrimental effects from the source and from the absorbing termination.

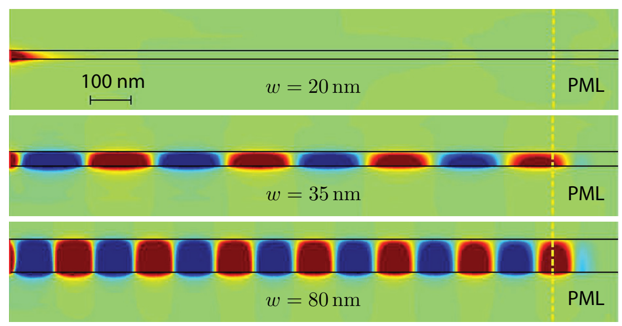

Fig. 4. Capped amplitude of the electric field at 300 THz inside the waveguide.

As an illustrating example, Fig. 4 shows the electric field amplitude at $f = 300\,\text{THz}$ inside a plasmonic HMSIW with SiO_2 layer height $h = 5\,\text{nm}$. For a width of $w = 20\,\text{nm}$, the mode is below cut-off, whereas for $w = 35\,\text{nm}$ and $w = 80\,\text{nm}$ the mode is propagating.

The phase constant for waveguides with height $h = 5\,\text{nm}$ and different widths w is plotted in Fig. 5. The cut-off frequency is clearly observed in this frequency range for $w = 15\,\text{nm}$, $20\,\text{nm}$ and $35\,\text{nm}$ showing that there can be only propagation for frequencies above the width-dependent cut-off.

The attenuation constant is plotted in Fig. 6. For $w = 15\,\text{nm}$, $20\,\text{nm}$ and $35\,\text{nm}$, as the propagating mode just above cut-off is a fast wave, radiation losses from the aperture are observed as strong attenuation which decreases very quickly with increasing frequency. For all waveguide widths, above a frequency of approximately 350 THz, the SPPs confinement properties at the dielectric

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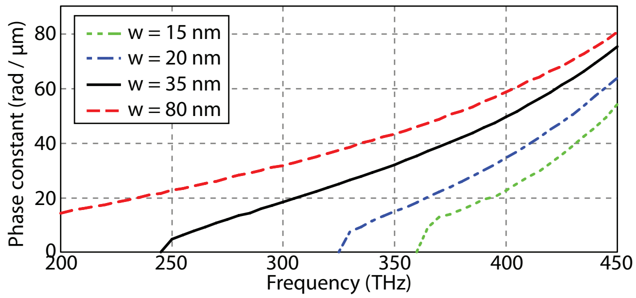

Fig. 5. Phase constant β (rad/μm) for different widths of the waveguide.

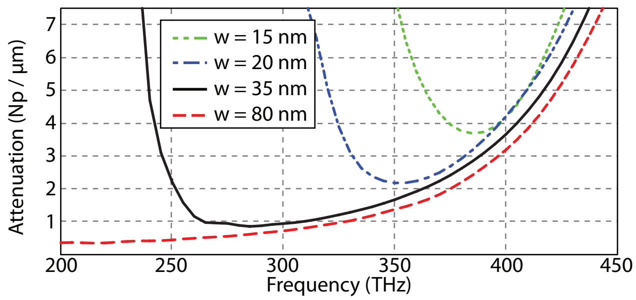

Fig. 6. Attenuation α (Np/μm) for different widths of the waveguide.

metal interface result in an increasing attenuation of the guided wave. Principally, there are two main aspects to be considered for the design:

1) The width of the waveguide determines the cut-off frequency of the fundamental mode. Just above the cut-off, a significant source of loss will arise from radiation from the aperture as in a microwave HMSIW [3]. Higher-order modes excited by fabrication and excitation imperfections may propagate for large waveguide widths. In contrast to the microwave range however, the height h will play a significant role in the propagation properties, with thinner heights resulting in a red shift of the cut-off frequency.

2) The usable frequency bandwidth is limited by the plasmonic effects of the metal. For higher frequencies, starting from around $350\,\text{THz}$, the propagation length decreases because of the damping of the SPP with increasing confinement. This can be deduced from Fig. 2 as the negative real part of the gold relative permittivity becomes comparable with the imaginary part. For plasmonic effects at higher frequencies, the material has to be changed, e.g. to silver [10], to allow propagation of visible light.

The compact size and nearly planar nature of the plasmonic HMSIW appears attractive for applications requiring short distance communication within limited space. Particularly, the proposed structure is a potential component for optical integrated circuits. Nevertheless, the general attenuation of these first plasmonic HMSIWs are still higher than the attenuation of other plasmonic waveguides, as for example the V-groove waveguide [11]. Optimal dimensions of the waveguide for best performance need to be further investigated, keeping in mind that the metal properties at optical frequencies complicate the simulation significantly and widen the solution space. The propagation characteristics depend on the waveguide width w, the intermediate dielectric layer height h and the gold thickness d. For a certain waveguide width w, the cut-off frequency decreases for thinner waveguide heights h. Additionally, the potential for creating bends and junctions has to be further investigated.

V. Conclusion

This paper has proposed a concept of a plasmonic waveguide inspired by HMSIW for on-chip short-distance optical communication. Full-wave FVTD simulations demonstrated propagation of guided waves when considering typical materials and dimensions achievable with modern nano-fabrication techniques. In addition to the waveguide width, optimization of the plasmonic HMSIW needs to include also the height of the guide as well as metals appropriate to sustain plasmonic effects in the frequency range of intended operation.

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