A directional coupling scheme for efficient coupling between Si$_3$N$_4$ photonic and hybrid slot-based plasmonic waveguides

D. Ketzaki$^{1,2}$, G. Dabos$^{1,2}$, J.C. Weeber$^3$, A. Dereux$^3$, D. Tsiokos$^{1,2}$ and N. Pleros$^{1,2}$

$^1$Department of Informatics, Aristotle University of Thessaloniki, Greece
$^2$Center for Interdisciplinary Research and Innovation, Aristotle University of Thessaloniki, Greece
$^3$Laboratoire Interdisciplinaire Carnot de Bourgogne, CNRS-Université de Bourgogne, Dijon, France

ABSTRACT
Slot-based plasmonic waveguides have attracted significant attention owing to their unique ability to confine light within nanometer-scale. In this context, enhanced localized light-matter interaction and control have been exploited to demonstrate novel concepts in data communication and sensing applications revealing the immense potential of plasmonic slot waveguides. However, inherent light absorption in the metallic parts included is such structures hampers the scaling of plasmonic devices and limits their application diversity. A promising solution of such issues is the use of hybrid plasmonic-photonic configurations. Hybrid slot waveguides have been introduced as the means to reduce such propagation losses while maintaining their functional advantages. In addition, their co-integration with low-loss photonic waveguides can enable the development of more complex structures with acceptable overall losses. In such scenario, light needs to be efficiently transferred from the photonic to the plasmonic components and/or backwards. Based on this rationale, in this work a hybrid slot-based structure is adopted to achieve highly efficient light transfer between photonic and plasmonic slot waveguides in the near-infrared spectrum region ($\lambda$=1550 nm). This transition is realized with the aid of a directional coupling scheme. For this purpose, a Si$_3$N$_4$ bus waveguide (photonic branch) is located below an Au-based metallic slot (plasmonic branch) forming a hybrid waveguide element. The combined configuration, as it is shown with the aid of numerical simulations, is capable of supporting two hybrid guided modes with quasi-even and odd symmetry allowing the development of a power exchange mechanism between the two branches. In this context, a new directional coupling structure has been designed which can achieve power transmission per transition over 68% within a coupling length of the order of just several microns.

Keywords: Plasmonics, hybrid slot waveguides, directional coupling, coupling efficiency.

1. INTRODUCTION
Plasmonic waveguides have attracted momentous research interest over the last years as the means to confine light in sub-wavelength regimes and overcome diffraction limit found in photonic integrated circuits (PICs). At the same time, their capability to guide both light and electric current enables the combination of optical and electronic communication on the same chip. However, the inherent absorption inside the metal layers of plasmonic waveguides introduces high losses impeding the broad utilization of solely plasmonic circuits. To fully exploit the advantages of planar plasmonic structures while maintaining practical power budgets in photonic integrated circuits, plasmonic waveguides should be selectively combined with low-loss photonic hosting platforms in planar integrated circuits. Such hybrid components can promise compact plasmo-photonic devices with superior performance in a range of applications including modulators$^1$, sensing elements$^2$, switches$^3$, antennas$^4$ etc. In this work, we propose a new hybrid plasmo-photonic waveguide configuration on silicon nitride (Si$_3$N$_4$) implementing a low loss, off-plane transition between a Si$_3$N$_4$ photonic waveguide and a plasmonic slot waveguide that can be potentially used as the fundamental transducer element in sensing applications. In this context, the optimization of the transducer waveguide is critical for maximizing optical field exposure and thus sensor sensitivity. The hybrid plasmo-photonic configuration stands out as an effective compromise between the purely photonic-based sensing elements$^5$, which exploit only the evanescent region of the guided field distribution, and the purely plasmonic configurations$^6$, which may be proved unsuitable for complex structures. In addition, the vast majority of hybrid waveguide structures which have been investigated during the last decade, the photonic hosting platform is based on silicon (Si)$^{7,8,9}$,
while we propose a hybrid waveguide based on a Si$_3$N$_4$ platform in order to further reduce overall losses and relax fabrication tolerances.

2. HYBRID WAVEGUIDE DESIGN AND SIMULATION

Our hybrid slot configuration consists of a Si$_3$N$_4$ bus waveguide (photonic part) and a gold (Au) slot waveguide (plasmonic part). The photonic waveguide is placed above a silica (SiO$_2$) layer, whereas low temperature oxide (LTO) is utilized between the two components (photonic and plasmonic) acting as the cladding of the photonic waveguide and as the spacer at the hybrid slot waveguide. The whole structure is cladded by water to optimally mimic the biosensing application environment (see Figure 1). This element exploits the directional coupling mechanism following the hybrid nature of the utilized waveguide, since it can support modes with field distributions both in its plasmonic and its photonic part. If properly designed, such modes can exhibit quasi even or odd symmetry allowing the power exchange between the two branches. This power exchange can be considered as the result of the beating between the two supported modes of different symmetry.

![Figure 1. Cross-sectional geometry of the hybrid plasmonic waveguide structure. The width of metallic slot ($w_{\text{slot}}$), the thickness of the LTO layer ($h_{\text{LTO}}$) and the width of the Si$_3$N$_4$ waveguide ($w_{\text{SiN}}$) are the three main design parameters under investigation.](image)

Our design target is to efficiently couple these two waveguide components (photonic and plasmonic) by combining them in a single hybrid structure. In this way, we expect to achieve the light transfer from the purely photonic part (Si$_3$N$_4$ bus waveguide) to the metallic slot in order to exploit it for sensing purposes. For this reason, the design analysis that follows is a two-step analysis: At the first step, an eigenvalue problem is solved at the cross-section of the waveguide under investigation to detect the hybrid modes of interest and examine their symmetry. In parallel, the necessary coupling length ($L_c$) is calculated and the overall geometry is optimized so that $L_c$ is simultaneously minimized. Next, a 3D geometry model of a potential sensing element is investigated in terms of 3D FDTD simulation analysis. At this step, the previously estimated coupling mechanism is verified and the coupling efficiency between the two waveguides is calculated. For the analyses described above, we focus our interest at the near infrared region of the frequency spectrum and more specifically at 1550 nm. The material properties in terms of refractive indices have been chosen as $n_{\text{SiO}_2}=1.46$, $n_{\text{LTO}}=1.46$, $n_{\text{Si}_3\text{N}_4}=2.02$, $n_{\text{Au}}=0.55-11.5i$ and $n_{\text{water}}=1.311-9.85\times10^{-5}i$.

2.1 2D eigenvalue analysis of the gold-based hybrid slot waveguide

Based on the rationale described above, the hybrid configuration under study has been initially examined in terms of 2D eigenvalue analysis. This investigation can give all the possible geometrical parameter combinations so that hybrid modes with even and odd symmetry can be supported. After a thorough study, in terms of parametrical investigation, the appropriate geometry setup ($w_{\text{slot}}=200\text{nm}$, Si$_3$N$_4$ width: $w_{\text{SiN}}=700\text{nm}$ and LTO thickness: $h_{\text{LTO}}=660\text{nm}$ with reference to Figure 1) has been chosen so that the modes of interest exhibit the necessary symmetry while leading to a small coupling length and minimum propagation losses in the slot waveguide area.
Figure 2 shows the electric field distribution for the quasi-even and odd modes that have been calculated through the eigenmode analysis. In this context, the approximate coupling length needed to efficiently transfer the power from the plasmonic to the photonic part has been calculated around 7μm using the following relationship:

\[ L_c = \frac{\pi}{\beta_{\text{even}} - \beta_{\text{odd}}} \]  

(1)

2.2 3D FDTD propagation analysis

The results extracted previously are verified through 3D FDTD electromagnetic simulations aiming at fine-tuning the geometrical setup and concurrently minimizing the beating length (consequently the overlapping coupling area between the two individual waveguides) and maximizing the power transfer from the photonic to the plasmonic part (and backwards). Figure 3(a) shows the 3D geometry model adopted for this analysis. In this 3D geometry model, the hybrid waveguide of interest is excited by an almost TE photonic mode with field distribution that has been calculated through an eigenmode analysis at the cross-section of the pure photonic part of the configuration (Figure 3(b)-(c)). This photonic mode, after propagating in the Si₃N₄ waveguide for several microns, is transformed to a hybrid mode right away meeting the gold slot above the bus waveguide.
In this area, where the two waveguides (plasmonic and photonic) coexist forming the hybrid structure the beating between modes of different symmetry enables the power exchange between the two branches. After a length of 7μm ($L_c$) which is considered the necessary distance for the power exchange to be maximized, the Si$_3$N$_4$ bus waveguide is interrupted. This interruption aims to maintain the coupled optical power entirely in the plasmonic slot preventing from any power coupling leakage between the photonic parts within the potential sensing area. Indeed, according to 3D FDTD simulations, such a hybrid configuration can efficiently transfer the light from the photonic to the plasmonic part (or backwards) with efficiencies over 68% per transition. Figure 4(a) shows the side view geometry of a structure with two photonic-to-plasmonic transitions and Figure 4(b) the field distribution plot depicting the light transfer.

More specifically, as it can be seen in Figure 4(b), the light is successfully transferred from the photonic Si$_3$N$_4$ waveguide to the plasmonic slot and back to the photonic part. To assess the efficiency of this transfer, in terms of power transmission, the propagating power has been calculated at two different planes along the direction of propagation, which are denoted as plane A and B in Figure 4(a). By means of a mode expansion technique, it was found that for a single transition at plane
A (photonic to plasmonic transfer) over 68% of the total input power is transferred to the plasmonic slot, whereas at the whole cross-section this power percentage is above 73%. After the Si$_3$N$_4$ waveguide interruption, the plasmonic mode propagates in the gold slot for a distance $d=4\mu$m (potential sensing area) and then the light is transferred back to the photonic part (Si$_3$N$_4$ waveguide). At plane B almost 40% of the total power has been calculated in the plasmonic slot which corresponds to a reduction of 3.5 dB of the input power. Table 1 summarizes the above calculations.

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<th>Power transferred at the plasmonic WG</th>
<th>Power at the whole cross-section</th>
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<tr>
<td>A</td>
<td>68.3 %</td>
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<tr>
<td>B</td>
<td>40 %</td>
</tr>
<tr>
<td></td>
<td>73.5 %</td>
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<td>44.6 %</td>
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Interestingly, after a single transition (calculation at plane A) the percentage of the power transferred to the plasmonic part, and thus available for sensing exploitation, relative to the power that is calculated in the whole cross-section is over 92%, showing the effectiveness of the proposed transition scheme. To qualitatively verify the excitation of the modes of interest at each propagation step, a calculation of the electric field distribution has been made at different planes towards the direction of propagation. Figure 4(c) depicts these distributions at three different planes transverse to the direction of propagation: At the input level, at a plane right after the Si$_3$N$_4$ interruption and at one right after the gold slot interruption. As it was expected, the light has been efficiently transferred from the photonic to the plasmonic mode of interest and backwards.

3. CONCLUSION

A new directional coupling configuration has been proposed to efficiently couple light between a photonic Si$_3$N$_4$ and an off-plane plasmonic Au-based metallic slot waveguide in the NIR spectrum region (at wavelength of 1550 nm). The individual photonic and plasmonic components have been appropriately combined to form a hybrid waveguide structure capable of supporting guided modes with quasi-even and odd symmetry. This feature led to the development of an efficient power exchange mechanism and coupling lengths of the order of several microns. More specifically, power transfer efficiencies over 68% have been achieved per transition (from photonic to plasmonic or backwards) within just 7$\mu$m of length. By exploiting the beneficial characteristics of both photonic and plasmonic technology, the proposed hybrid slot-based waveguide can be used as the sensing transducer element in a Si$_3$N$_4$-based integrated sensor.

ACKNOWLEDGEMENTS

This work is supported by the European H2020 ICT PLASMOfab (no.688166) project.

REFERENCES


