Design of plasmon waveguide with strong field confinement and low loss for nonlinearity enhancement

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Abstract—**We propose a new hybrid dielectric and plasmonic waveguide offering an ultra high nonlinear coefficient γ = 4.7× 10^9 $W^{-1}km^{-1}$ which is 4 orders larger than conventional silicon waveguide with a propagation loss of 0.036 dB/µm.**

Keywords-silicon based; plasmon; nonlinearity; confinement; loss.

I. INTRODUCTION

Nanophotonics based on surface plasmon-polaritons (SPPs) is attracting increasing attentions in recent years. The SPP modes are capable of confining lights to nanoscale that is far beyond the diffraction limitation. However the application of SPP is limited due to its high propagation loss caused by the ultra high absorption in the metal. Thus it is highly desired to design a plasmon waveguide with strong field confinement and low propagation loss.

For conventional plasmon waveguides, the long-range SPP[1] mode does not exhibit nanoscale field confinement despite its long propagation length, which is not suitable in nonlinear applications. In recent years, several plasmon waveguides capable of nanoscale field confinement have been introduced, including wedge waveguide, groove waveguide, dielectric-loaded waveguide, slot waveguide and hybrid-waveguide[2]. Among them, hybrid waveguide conductor-gap-dielectric (CGD)[3] shows a relatively better field confinement and lower loss. However the loss increases though the effective mode area scales down, which limits its nonlinear applications. In this paper a new design of silicon based hybrid plasmon waveguide (polymer surrounding hybrid plasmon waveguide (PS-CGD)) is proposed to achieve not only ultra high nonlinear coefficient γ, but also low propagation loss. The nonlinearity is 3 orders higher than conventional silicon waveguide (CSW), and the propagation loss is only ten percent of that of the conventional metal/silicon SPP. We further propose an improved step hybrid plasmon waveguide with 4 orders larger nonlinear coefficient than CSW and low propagation loss.

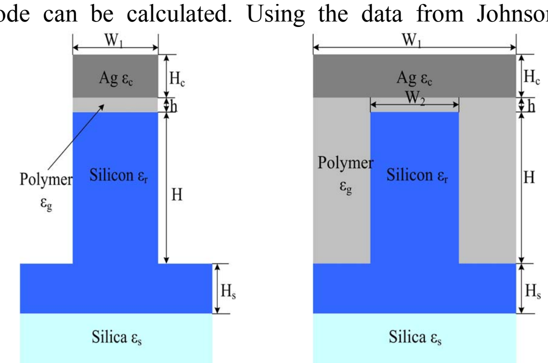
II. WAVEGUIDE STRUCTURE

For a conventional hybrid CGD waveguide[5] in Fig.1 (a), the plasmonic mode with effective index N_1 is strongly confined in the polymer gap with h thickness, due to the coupling between the SPP mode and silicon waveguide mode. However the loss exponentially increases with the decrease of the waveguide width, as there is more power distributed in the metal instead of silicon waveguide with the smaller waveguide width. To enhance the nonlinearity a trade-off between the nonlinear coefficient and propagation loss has to be made.

To solve this problem, a PS-CGD structure is proposed. Fig.1 (b) shows the schematic of the proposed hybrid plasmon waveguide. Region-regular Poly(3-Hexy1Thiophene) (RR-P3HT)[4] with high nonlinear index $n_2 = 2.9\times10^{-17}$ m^2/W is introduced to achieve high nonlinearity. The hybrid waveguide consists of a bottom silicon waveguide with a dimension of $W_2 \times H$ and a top Ag slab with a dimension of $W_1 \times H_c$. The Ag slab is aligned vertically with respect to the silicon waveguide but separated from it with a RR-P3HT polymer gap. The thickness of the polymer layer is h at the silicon ridge region and h+H at the ridge surrounding region. PS-CGD waveguide can be regarded as a combination of two CGD waveguides including silicon ridge surrounding plasmon waveguide (SRSPW) with a gap thickness of h+H, and silicon ridge plasmon waveguide (SRPW) with a gap thickness of h.

III. SIMULATION RESULTS AND ANALYSIS

Using the commercial finite-element package FEMLab from COMSOL, the magnitude of electric field E of plasmonic mode can be calculated. Using the data from Johnson and



(a) (b)

Figure 1. (a) Structures of CGD waveguide[5]; and (b) PS-CGD

Christy[7], the refractive index of Ag is 0.1443+11.57i at 1550 nm. The refractive indices are 3.455 and 1.6 for silicon and RR-P3HT, respectively, at 1550 nm.

Fig.2 shows that the electric field is strongly confined in the 5-nm thick polymer layer. The structural parameters used in the simulations are as follows: W_2 =50 nm, H = 300 nm, h = 5 nm, H_c = 100 nm, H_s = 200 nm, W_1 = 300 nm. To compare with the CGD waveguide, we vary the silicon rib width W_2 from 5 nm to 400 nm to obtain the corresponding loss curves as provided in Fig.3. For the CGD waveguide[5] (triangle), the loss increases rapidly with the decrease of waveguide width as there is less field distributed in the silicon waveguide resulting in higher loss though the effective mode area decreases. In PS-CGD plasmon waveguide, the loss significantly reduces comparing with CGD waveguide as the rib width decreases. Due to the large gap thickness (h+H) of SRSPW, SRSPW is considered as a Ag/RR-P3HT interface SPP waveguide with effective index N_2. SRPW is considered as CGD waveguide with effective indice N_1[5]. The effective indices N_1 and N_2 fulfill the following inequations[3]: $Re(N_1) > Re(N_2)$, $Im(N_1) > Im(N_2)$. According to the effective index analysis method[6], the light is essentially confined to the ridge region laterally. The field decays exponentially in the polymer surrounding region. The total effective index N follows to the following inequations: $Re(N_1) > Re(N) > Re(N_2)$, $Im(N_1) > Im(N) > Im(N_2)$[6]. With narrower silicon width, according to the effective index analysis theory[6], the effective index N is closer to N_2, thus reducing the loss. Meanwhile, the field is still confined in the 5nm-thick polymer gap to maintain the same effective mode area. According to the exponential decay formula of $\exp(-(k_0N - k_0N_2)\times L)$ in the polymer at the two sides of rib, when the rib width decreases, the real part of effective index decreases, reducing $(Re(N) - Re(N_2))$. Therefore the field distribution in polymer at the two sides of rib becomes larger, which can compromise the reduction

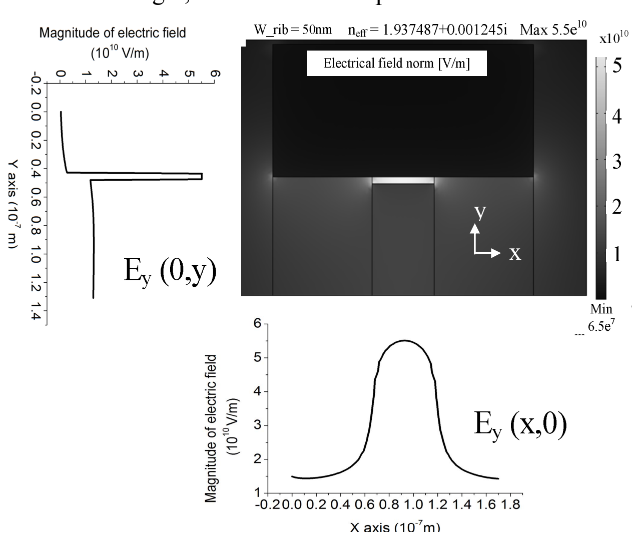


Figure 2. Electric field profiles of polymer surrounding hybrid plasmon waveguide in x-y plane

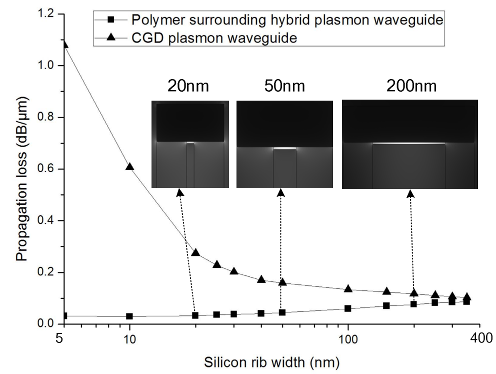


Figure 3. Propagation loss of two types of hybrid plasmon waveguides versus the silicon rib width: triangle, conventional hybrid plasmon waveguide; square, polymer surrounding hybrid plasmon waveguide

of the power in the silicon waveguide and eventually reduces the total loss (imaginary part of effective index). The insets in Fig.3 show the field distribution of the major components E_y of the electrical field. From the three inset figures one can see that there is more optical power in the polymer at the two sides of rib as the rib width decreases compared with CGD structure.

When the width becomes very small (< 20 nm), less power is confined in the 5-nm thick polymer layer, enlarging the effective mode area but mitigating the propagation loss. We define a normalized nonlinear phase shift to find the optimal trade-off rib width: γL_{eff} with the same input power as shown in Fig.4. $\gamma = n_2\omega/(cA_{eff})$, where n_2 is the nonlinear index of polymer RR-P3H7, c is the light velocity in the vacuum, A_{eff} is the effective mode area, L_{eff} is the propagation length defined as the distance for the intensity to decay by a factor of 1/e .

With a silicon rib width of 20 nm, the highest γL_{eff} is achieved with a nonlinear coefficient $\gamma = 11.75\times10^8\ W^{-1}km^{-1}$, which is 2000 times larger than conventional silicon waveguide with a 0.033 dB/μm propagation loss corresponding to 130-μm propagation length.

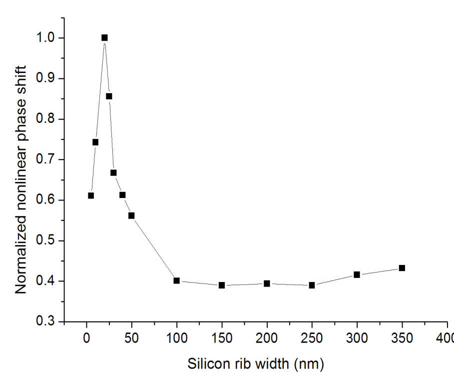


Figure 4. Normalized nonlinear phase shift versus silicon rib width of polymer surrounding hybrid plasmon waveguide

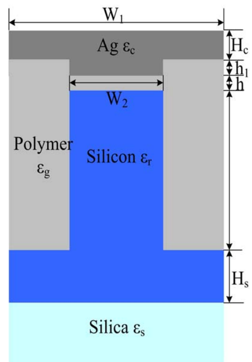
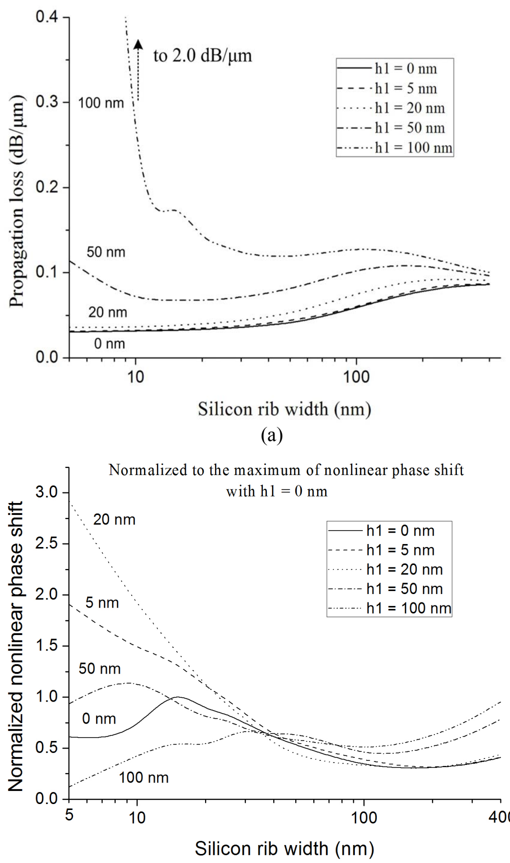


Figure 5. Step hybrid plasmon waveguide structure

IV. IMPROVED WAVEGUIDE STRUCTURE

We further propose an improved hybrid plasomonic waveguide structure with an additional step of Ag in the ridge region in Fig.5. The height of step h_1 can be adjusted to change the coupling between the plasmonic modes in the ridge region and the ridge surrounding region. With larger h_1, the coupling becomes weaker, resulting in higher loss but more confined mode in the h thick polymer layer. A h_1 value can be found for the best coupling situation to achieve optimal normalized nonlinear phase shift.



(b)

Figure 6. Loss (a) and normalized nonlinear phase shift (b) versus step height

Fig.6 shows the simulation results of loss and normalized nonlinear phase shift versus step height h_1 with the same structural parameters as the PS-CGD. For the step height h_1 smaller than 50 nm, the loss is almost the same as the PS-CGD waveguide, however an edge plasmonic mode is induced to confine optical power in the 5-nm thick polymer layer, increasing the normalized nonlinear phase shift. With large step height h_1 (> 50 nm), the loss grows exponentially with the decrease of ridge width caused by the weak coupling, which is the same as CGD waveguide, leading to the reduction of normalized nonlinear phase shift.

The highest γL_{eff} is achieved at h_1 = 20 nm with a silicon ridge width of 5 nm. The normalized nonlinear phase shift triples compared to the PS-CGD waveguide. The nonlinear coefficient γ reaches $4.7\times10^9\,W^{-1}km^{-1}$ and the propagation loss equals 0.036 dB/μm.

In conclusion, we proposed a PS-CGD waveguide with nonlinear coefficient γ of $11.75\times10^8\,W^{-1}km^{-1}$ and propagation loss of 0.033 dB/μm. Furthermore the step hybrid plasmon waveguide exhibits better performance in the nonlinear coefficient and propagation loss compared with CGD and PS-CGD waveguides. The best trade-off is achieved at silicon ridge width of 5 nm and step height of 20 nm, with a high nonlinear coefficient γ of $4.7\times10^9\,W^{-1}km^{-1}$ and low loss of 0.036 dB/μm.

ACKNOWLEDGMENT

This work was supported by NSFC (60777040) and the 863 High-Tech program (2009AA01Z257).

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