Ultra-Compact Directional Coupler Using Hybrid Plasmonic Waveguide with Dual Metallic Layers

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***Abstract*—We analyze hybrid plasmonic waveguides with metallic layers on two sides. Confinement of closely stacked metal induces large difference of effective indices of vertical even and odd modes. This phenomenon can be utilized as ultra-compact vertical directional coupler. Simulation shows directional coupling can be achieved in less than $1\ \mu$m.**

I. INTRODUCTION

Miniaturization and loss reduction have been two major issues among various challenges of photonic circuit design. Conventional dielectric waveguides are not proper for high-density on-chip integration due to relatively weaker field confinement and large size. Plasmonic waveguides [1] have been proposed for nano-scale optical guided wave, but their application is limited due to high propagation loss. Therefore, hybrid plasmonic waveguides (HPWG) has been an attractive research due to their great compromise of miniaturized dimensions and low-loss propagation for on-chip integration [2]. These features make HPWG a promising candidate for future photonic circuit technology. However, even with nanoscale guiding capability, it is essential that all photonic modules must be highly compact. For nanoscale light source, several hybrid plasmonic laser modules have been reported with experiment results [3], [4]. Beam splitters based on multimode interference (MMI) and Y-branch have also been analyzed. A compact directional coupler of two laterally positioned HPWG has also been demonstrated [6]. In this paper, we propose an alternative scheme of compact directional coupler based on high-order guided mode in area between two metal layers for enhanced coupling effect. All simulation parameters are based on [2]. The propagation characteristics of guided modes for the coupling process will be numerically analyzed [7] for explanation.

II. CONCEPT AND SIMULATION RESULTS

In dual waveguide configuration, directional coupling effect can be considered composition of even and odd modes. The coupling length can be calculated by $L_c = \pi/k_0|\Re\{n_{\text{eff}}(\text{even}) - n_{\text{eff}}(\text{odd})\}| = \pi/k_0|\Re\{\Delta n\}|$, where n_{eff} is equivalent index of each guided mode. Therefore, coupling length can be reduced by a structure with larger $\Re\{\Delta n\}$. For metallic waveguide, its strong confinement allows higher-order guided plasmonic mode with major field in subwavelength dielectric region. Due to close proximity of two metal layers, we expect that transverse field variations of even and odd modes are significantly different, and this will lead to increased $\Re\{\Delta n\}$.

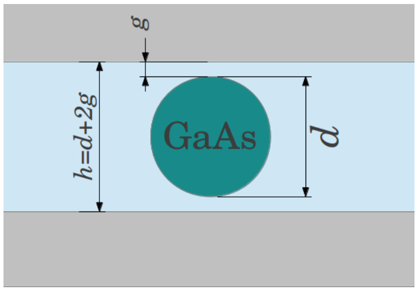
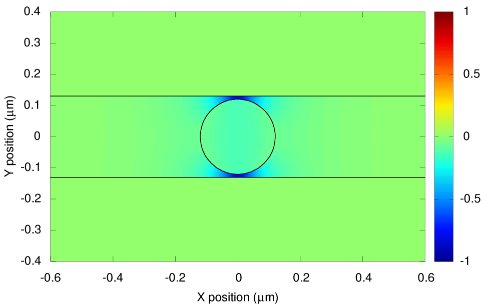


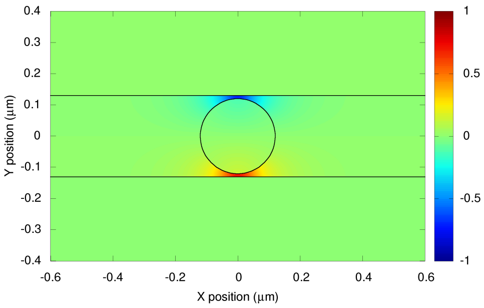
Fig. 1. Schematics of hybrid plasmonic waveguide.

We apply this concept to a hybrid plasmonic waveguide with circular dielectric core, which is mostly based on structure proposed in [2]. From schematic of Fig. 1, we add additional metal layer on top of dielectric core with identical gap size to form vertical symmetry. Gap size is set to 10, 20, or 30 nm. Coupling length and propagation distances of even and odd modes with different GaAs core diameters and gap sizes are shown in Fig. 3 and 4, respectively. From Fig. 3, structures with larger gap or core sizes have advantages on propagation distance due to less field penetration into metal region. Furthermore, as diameter of GaAs core increases, more field is confined in core region and surface plasmonic effect is reduced. Note that with even larger core diameter, the waveguide is similar to a conventional dielectric waveguide. On the other hand, the core size must be sufficiently large for guiding in extremely thin gap. As illustrated in Fig. 3, odd mode guiding fails when g is 10 nm and d is less than 240.

Comparison of geometry setting and coupling are shown in Fig. 4. Using thinner gap gives shorter coupling length for compact design with diameter less than 340 nm. When distance between two metal layers h are very close and dielectric core is too small for field confinement, Δn is then dominated by h. From Fig. 4, for example, we define structures with (d, g) equals to $(220, 30)$, $(240, 20)$, and $(260, 10)$ nm as cases A, B, and C, respectively. These cases have identical h of 280 nm



(a) Even mode



(b) Odd mode

Fig. 2. E_y field distribution of hybrid plasmonic waveguide modes with circular GaAs core. Diameter d and gap g are 240 and 10 nm, respectively.

and close coupling lengths. When d is large enough for field confinement in dielectric core, overall coupling characteristics is more susceptible to interaction of cladding field distribution of dielectric mode and metal surface. If field is weakly confined in core and gap is very thin, surface plasmonic effect can still effectively determine the coupling length. However, larger gap size indicates less surface plasmonic interaction with field in cladding, leading to saturation-like coupling results for $(d, g) = (400, 30)$ nm. For design consideration, comparison of ratio L_c/L_{odd} is also shown in Fig. 4. The L_{odd} is chosen for benchmark due to larger propagation loss. Except the case of $(d, g) = (220, 10)$ nm, the L_c/L_{odd} ratios exceed 50 for all other cases. This indicates that efficiency degradation of coupling by the even-odd mode beating due to modal loss is very low. It also allows multiple cascading coupler design with minimal loss penalty.

III. CONCLUSION

We have proposed and analyzed an alternative configuration of dual hybrid plasmonic waveguide for directional coupler application. Coupling length can be easily shrinked to sub-micron scale. Compared with propagation loss, the directional coupling is achieved in very short distance and significant loss is avoided. Other design to improve device compactness and loss profile is now in progress.

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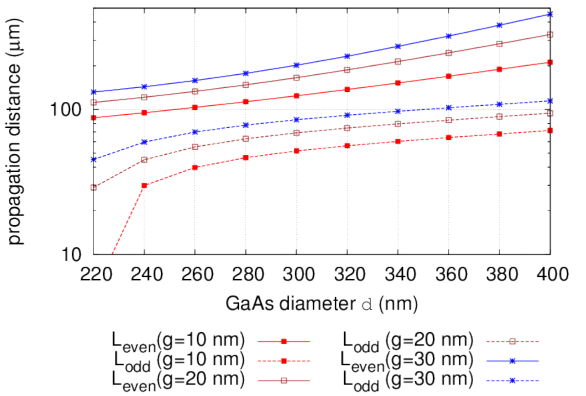

Fig. 3. Propagation length of even and odd modes of hybrid plasmonic waveguide.

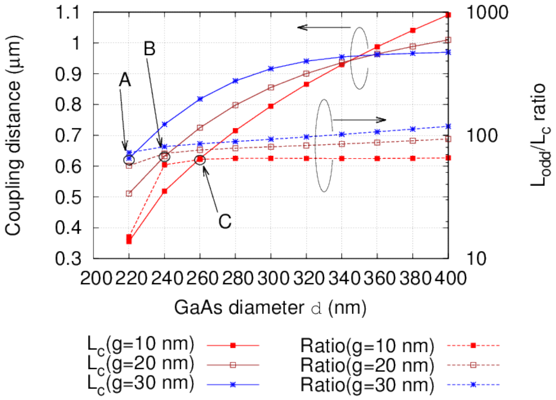

Fig. 4. Coupling length of even and odd modes and L_{odd}/L_c ratio of hybrid plasmonic waveguide.

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