

# Transmission Characteristics Analysis Of a Directional Coupler Based on Hybrid SNIMS Plasmonic Waveguide

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**Abstract**—We numerically simulate a directional coupler based on hybrid SNIMS (semiconductor-nanowire-insulator-metal strip) plasmonic waveguide using COMSOL. The distributions of electromagnetic field and longitudinal energy flux density when only fundamental mode propagates in waveguides are analyzed. The dependences of coupling length and maximum transfer power on the distance of two parallel waveguides are discussed. The results show that the longitudinal energy flux density in the waveguides concentrates mainly on the lower edge of Si nanowire, which helps increase the coupling strength. At the same time, the coupling length of the directional coupler can decrease efficiently by reducing the distance of two parallel waveguides. This subwavelength directional coupler can be used for optical integrated circuits.

**Keywords**—directional coupler; transmission characteristics; plasmonic waveguide; SPP; COMSOL

## I. INTRODUCTION

Optical devices based on Surface Plasmon Polariton (SPP) can break through the diffraction limitation that traditional devices have to face. SPP has great potential in the realization of nanometer photonic integrated devices. So far, the novel nanometer optical devices based on SPP, such as beam splitter [1], reflector [2], filters [3, 4], Mach-Zehnder interferometer [5] and waveguide ring resonator [4], attract people's widespread attentions.

Optical directional couplers (ODCs) are basic optical components. They are primarily used as power splitters, switches, wavelength selective filters, modulators, channel interleavers and so on. Recently, researches of ODC based on SPP have been reported. Han Zhanghua et al. designed an ultra-compact  $2 \times 2$  port optical directional coupler, and obtained high electric intensity distribution and very strong localized field [5]. Zhao huawei et al. proposed a novel SPP optical directional coupler and studied a

position offset between the extreme values of the two output ports. It showed that the total output power of the two output ports decreases gradually with the increasing of coupling region length [6]. Chen Pixin's simulations show that power can be periodically transferred between its two Metal-Insulator interfaces while power is injected asymmetrically [7]. Veronis Georgios group theoretically investigated the power transmission of compact couplers between high-index contrast dielectric slab waveguides and two-dimensional metal-dielectric-metal subwavelength plasmonic waveguides. They gained a transmission efficiency of  $\sim 70\%$  at the optical communication wavelength [8].

Our group reported [9] that the coupling length of directional coupler based on hybrid SNIMS plasmonic waveguide has been reached  $2.2 \mu\text{m}$ , which meets the requirements of the nanometer photonic integration. In this paper, transmission characteristics of directional coupler based on hybrid SNIMS plasmonic waveguide are further investigated. We numerically simulate different distances of two parallel waveguides coupler using COMSOL, and analyze the distributions of electromagnetic field and longitudinal energy flux density when only consider fundamental mode propagates in waveguides. At the same time, the dependences of coupling length and maximum transfer power on the distance of two parallel waveguides are studied.

## II. COUPLER STRUCTURE

We proposed a directional coupler structure based on hybrid SNIMS plasmonic waveguide, its model schematic is shown in Fig. 1(a). A metal film layer is placed on a glass substrate, a silica covering layer is on the metal layer, the silica covering layer loads two parallel cylinders silicon nanowire, which are regarded as two adjacent hybrid waveguides. We set the two waveguides symmetrical and parallel to each other. The thickness of

the silica covering layer is  $h$ , the radius of the silicon nanowire is  $r$ , the distance of the two parallel waveguides is  $d$ .

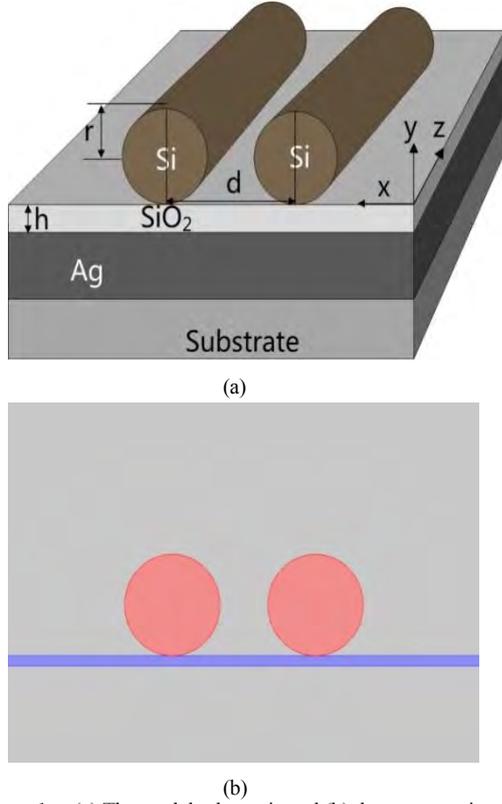


Figure 1. (a) The model schematic and (b) the cross-section view of the directional coupler

Fig .1(b) is the cross-section view of the directional coupler. We use telecommunication wavelength 1550 nm as incident wave to excite the SPPs. The refractive index of silicon nanowire and silica covering layer are  $\epsilon_{Si} = 12.25$ ,  $\epsilon_{SiO_2} = 2.25$ , respectively. We select Ag as the metal material, its refractive index is  $\epsilon_{Ag} = -129 + 3.3j$  under the incident wave. All the components are surrounded by air ( $\epsilon_{air} = 1$ ) and placed on a glass substrate with a thickness more than 200 nm (the substrate is not shown in the cross-section view). According to ref. [10], SPP's skin depth in silver is always around 20 nm. We set the thickness of the silver film 100 nm so no impact of silver film thickness would be put on the SPP inside the silica nanosheet. In our simulations, we set the propagation direction along z-axis. The dominant electric field must point in the z-direction to ensure excitation of the SPP mode along the waveguide.

### III. CHARACTERISTICS ANALYSIS OF THE DIRECTIONAL COUPLER

Our group has analyzed even and odd mode of the directional coupler. In order to further investigate its transmission characteristics, we first simulate the electric field distribution of the directional coupler at the telecom wavelength 1550 nm by using COMSOL. The electric intensity distributions in x-axis and y-axis are shown in Fig.2, respectively.

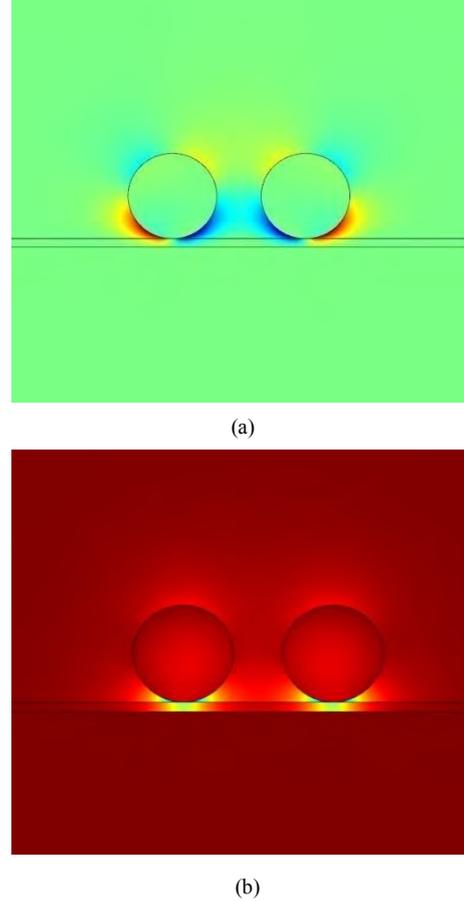


Figure 2. The electric field intensity distribution (a)  $E_x$  and (b)  $E_y$

From Fig .2, we know that the electric field intensity is antisymmetric component in x-axis and symmetric component in y-axis. Meanwhile, we obtain high electric field intensity distribution and very strong localized field in y-axis. Obviously, the y-axis component is the dominant, so the x-axis component often has been ignored.

Then, we simulate the magnetic-field distribution in x-axis and Poyting vector  $S_z$ , as shown in Fig .3 and Fig .4.

From Fig .3, one can observe that the light power mainly distributes in the waveguides. Besides, we can see that a large proportion of the light power still firstly couples to the near side interface though  $d$  has changes a lot (from 300 nm to 600 nm). Fig .4 shows the distribution of electromagnetic energy flux density (Poyting vector)  $S_z$  at  $d=400$  nm with  $r=150$  nm. Here  $S_z = E(x, y) \times H(x, y)$ . We can find that the energy intensity concentrates mainly on the lower edge of silicon nanowire. This helps to increase the SPP's evanescent field between a silica nanosheet and around dielectric, and thus improve the coupling efficiency.

With the SPPs propagation along z-axis, the energy transfer between the two waveguides. The power of one waveguide reduces gradually and increases gradually on the other waveguide. Because of the transmission loss, when the power of one waveguide reaches the maximum value, the other waveguide's power doesn't reduce to the minimum.

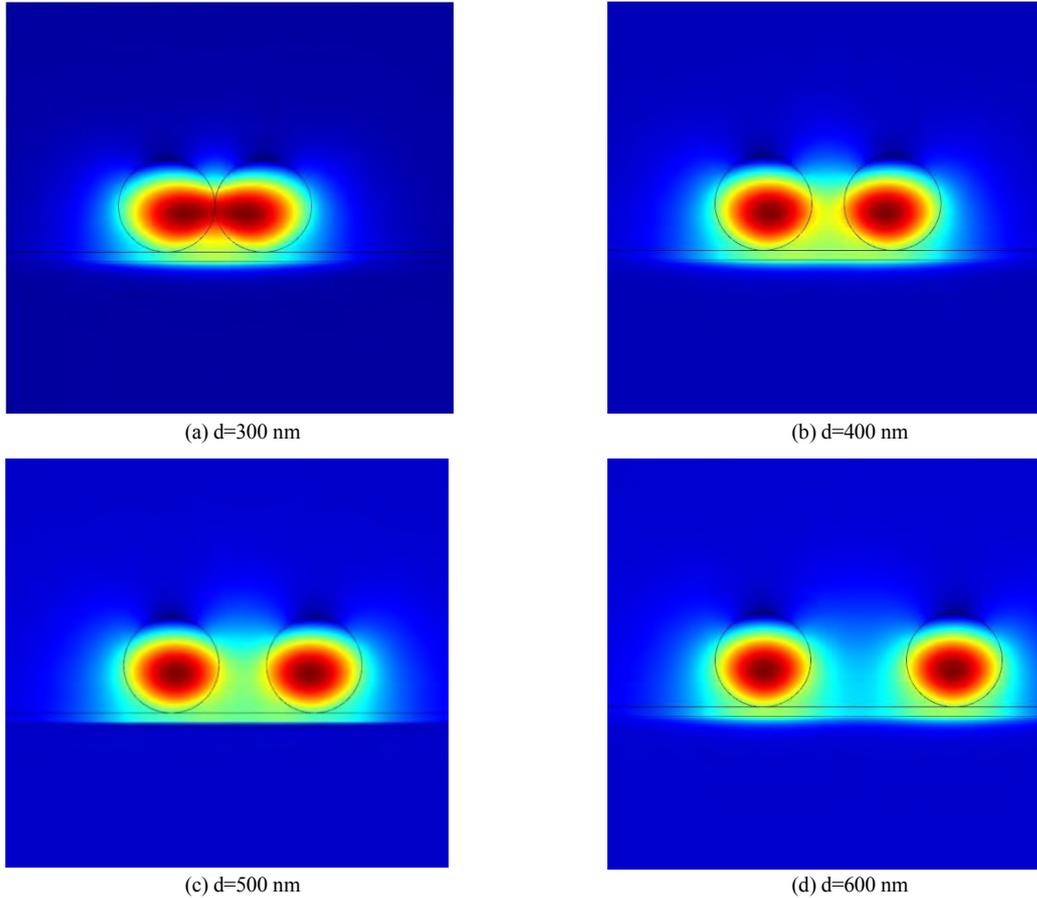


Figure 3. The contour profiles of magnetic field  $H_x$  respectively for  $d=300, 400, 500,$  and  $600\text{nm}$  when  $r=150\text{ nm}$

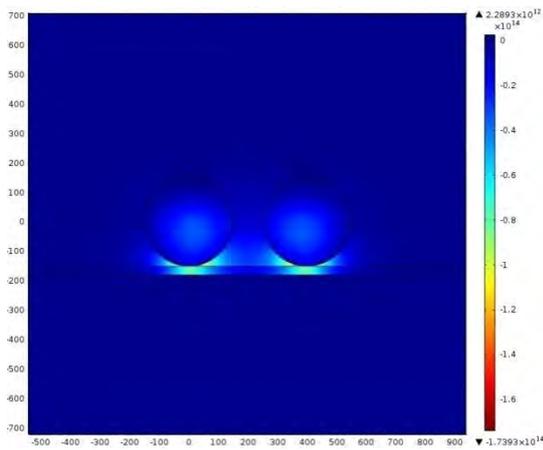


Figure 4. Poynting vector  $S_z$

When a light wave is injected into one waveguide, transfer power is the power that the other waveguide obtains. It is an important parameter of directional coupler. By integral computation of Poynting vector, the dependences of maximum transfer power on the distance of the two parallel waveguides are shown in Fig .5. It shows that the maximum transfer power increase with the reduction of the distance of the two parallel waveguides. So the coupling strength can be increased by reducing the distance of the two parallel waveguides.

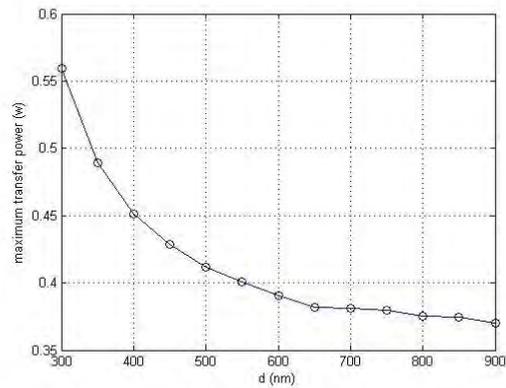


Figure 5. Dependence of maximum transfer power  $P_{\max}$  on the distance of the two parallel waveguides

#### IV. CONCLUSION

A kind of directional coupler based on hybrid SNIMS plasmonic waveguide is proposed and the relative characteristics have been simulated. The distribution of electromagnetic field and longitudinal energy flux density when only consider fundamental mode propagates in waveguides are analyzed. By studying the dependences of coupling length and maximum transfer power on the distance of the parallel waveguides, we believe that reduction on the distance of the parallel waveguides can improve coupling efficiency and shorten the coupling length. In addition, increasing the distance of the parallel

waveguides can reduce coupling strength, which boosts the integration level of the SPP integrated optical circuit. The simulation results lay a foundation to design and manufacture the SPP directional coupler.

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