Plasmonic waveguides and resonators for optical communication applications

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Abstract

Photonic circuits can transmit data signals in a much higher speed than conventional electronic circuits. However, miniaturization of photonic circuits and devices is hindered by the existence of light diffraction limit. A promising solution to this problem is by exploiting plasmonic systems for guiding and manipulating signals at optical frequencies. Plasmonic devices are generally composed of noble metals and dielectrics, whose interfaces can confine surface plasmon polaritons, a hybrid wave that is free of diffraction limit. Plasmonic waveguides and devices are serious contenders for achieving next-generation photonic integrated circuits with a density comparable to the electronic counterpart.

This thesis addresses the design issues of passive plasmonic devices which are critical for realization of photonic integration, including plasmonic waveguides, splitters, couplers, and resonators, investigated with both the finite-difference time-domain method and the finite-element method. In particular we present, firstly, a coupler which efficiently couples light between a silicon dielectric waveguide and a hybrid plasmonic (HP) waveguide. A coupling efficiency as high as 70% is realized with a HP taper as short as 0.4µm. The experimental result agrees well with the numerical simulation. Secondly, we numerically investigate and optimize the performances of 1 × 2 and 1 × 3 HP multimode interferometers (MMIs), which split light from a silicon waveguide to multiple HP waveguides. Total transmission over 75% can be achieved in both cases. Thirdly, we study the coupling and crosstalk issues in plasmonic waveguide systems. Several methods for crosstalk reduction are proposed. Finally, HP nanodisk micro-cavities are designed and are numerically characterized. With a radius of 1µm, a high quality factor of 819 and a high Purcell factor of 1827 can be simultaneously achieved, which can be useful for realizing efficient nano-lasers.
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VII. Bozena Jaskorzynska, **Yi Song**, and Min Qiu, "Tradeoff between mode confinement, loss, and cross-talk, for dielectric and metal slot waveguides", Photonics Letters of Poland, 1(4), 172-174, 2009.

List of Publications not included in the thesis, but related:


List of Acronyms

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<td>3D</td>
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<tr>
<td>MoM</td>
<td>Method of Moment</td>
</tr>
<tr>
<td>PML</td>
<td>Perfect Matched Layer</td>
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<tr>
<td>SOI</td>
<td>Silicon-on-Insulator</td>
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<td>TM</td>
<td>Transverse Magnetic</td>
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Chapter 1

Introduction

1.1 Background

In the last two decades, there have been a number of significant developments in the photonics industry and research. Compared with conventional electronic circuits, there are patent advantages in the data storage and delivery for photonic circuits. Therefore, more and more attentions have been paid to photonic devices, such as waveguides [1–5], resonators [6–8] and their integrations with electronic devices.

Although superior in the capability of signal delivery, the miniaturization is always a difficulty for photonic devices. As a widely used optical interconnect, the optical fiber can efficiently deliver signals about three orders of magnitude larger than that of electronic devices; meanwhile, its dimension is several hundred times larger than that of electronic devices. It is mainly caused by the diffraction limit that reducing the dimension of a photonic device to be smaller than half wavelength (typically several hundred nanometers in optical telecommunication regime) becomes a challenge. The huge mismatch between the electronic and photonic devices blocks the realization of high density integration of these two technologies.

To solve such a problem, a potential method has been proposed in recent years by utilizing the so-called plasmonic devices [9–12]. By guiding the electromagnetic wave at a dielectric-metal interface, plasmonic devices have the capability of confining light in a deep subwavelength scale. Thus, plasmonics could have the advantages of both the photonics with high-speed data delivery and the electronics with miniaturized dimension simultaneously. Besides the excellent mode confinement, plasmonic devices have another significant advantage: the strong enhancement of the electromagnetic field. It is followed by many special physical properties, such as optical gradient forces [13], surface enhanced roman scattering (SERS) [14] which are widely applied in optical trapping [15], nonlinear optics [16], etc. Among these two advantages, we mainly focus on investigating of the mode confinement and corresponding devices as plasmonic waveguides and resonators in this thesis.
In the recent years, several different types of plasmonic waveguides have been proposed, such as metallic nanoparticle chain waveguides [17, 18], metallic wire or stripe waveguides [19,20], plasmonic channel or wedge waveguides [21–23], plasmonic slot waveguides [24], dielectric-loaded plasmonic waveguides [25], hybrid plasmonic (HP) waveguides [26–30], etc. In general, these plasmonic waveguides have a trade-off between the mode confinement and the propagation length [31]. For example, the metallic wire or stripe waveguides have relatively large propagation lengths of several hundred micrometers or even several millimeters, however it is difficult for them to realize subwavelength mode confinement; and for plasmonic channel or slot waveguides with deep-subwavelength mode confinement, the propagation lengths are usually only several micrometers. Among them, the hybrid plasmonic waveguide is found to be relatively superior: it has a large propagation length with a subwavelength mode confinement. That is why we choose HP waveguides as the major research topic in this thesis.

In the integrated nanophotonic system, waveguides are very important components which can be applied to interconnect all the other components. As an extension, several other devices based on waveguides should also be referred: to efficiently couple optical signals from a dielectric waveguide to a plasmonic waveguide, a tapered structure or a directional coupler is necessary; to split light from one dielectric waveguide to several plasmonic waveguides, a Y-splitter or a multimode interference (MMI) is a good choice. Meanwhile, the resonators are also important components in nanophotonics which are widely utilized as modulators or light sources. Although similar to other nanophotonic devices, there is a prominent difference in plasmonic devices as the existence of the propagation loss (Ohmic loss) which should be carefully considered in the design of plasmonic devices. On the other hand, with the excellent mode confinement there are many special functions which can only be realized in plasmonic devices such as extremely high Purcell factor for laser cavity designs.

For another advantage of plasmonic devices of the strong enhancement of the electromagnetic field, there are also many important applications, such as optical trap, SERS, bio-sensor, etc. However, we will not study those devices and functions extensively in this thesis.

1.2 Thesis Outline

The major topic of the thesis is the design and simulation of the plasmonic waveguides and resonators for optical communications. With detailed analyse of the physical properties and numerical optimizations, the corresponding plasmonic devices are systematically studied. The thesis is organized in mainly two parts:

The first part includes Chapter 2 and 3. In Chapter 2, we introduce the physical properties of the surface plasmon polaritons and compare them with conventional
optics. In Chapter 3, we briefly summarize two different numerical methods used in this thesis: the Finite Element Method (FEM) which is used to obtain the eigenmodes of the electromagnetic modes in waveguides; and the Finite-Difference Time-Domain (FDTD) Method which is used to study the propagation of the electromagnetic wave in time domain.

The second part includes Chapter 4, 5 and 6. In Chapter 4, we design and characterize the properties of a plasmonic taper coupler and a multimode interference used to interconnect dielectric and plasmonic waveguides. In Chapter 5, we analyze and compare the properties of coupling and crosstalk between different dielectric and plasmonic waveguides, and modifications are proposed to reduce the crosstalk between plasmonic waveguides. In Chapter 6, we study the properties of the designed plasmonic nanodisk cavities. With optimization, a high $Q$ factor and a high Purcell factor can be realized simultaneously.
Chapter 2

Surface Plasmon Polariton

Surface plasmon polaritons (SPPs) are electromagnetic oscillations at the interface between a dielectric layer and a metallic layer [32, 33]. Due to the existence of metal, the electromagnetic fields can be well confined at the interface, which can be exploited for subwavelength mode confinement. However, the large Ohmic loss in metal leads to a large propagation loss, for which the propagation length of a surface wave is relatively smaller than normal electromagnetic waves. In this chapter, we will investigate the properties of surface waves initiated from the Helmholtz equation and Maxwell’s equations [34].

2.1 Surface Modes

The surface plasmon polaritons exist at the interface between a dielectric and a metallic layer. For simplicity, we set the geometry to be a two-dimensional structure as shown in Fig. 2.1(a).

The interface is localized at the plane \( z = 0 \) with the electromagnetic wave propagation in the \( x \) direction and there is no spatial variation in \( y \) direction. According to the Helmholtz equation

\[
\nabla^2 \vec{E} + k^2 \vec{E} = 0
\]

(2.1)

where \( k \) is the wave vector of the propagation wave. With different polarizations, two different modes can be supported: the transverse magnetic (TM) modes, for which only the components \( E_x, E_z, H_y \) exist; and the transverse electric (TE) modes, for which only the components \( E_y, H_z, H_x \) exist.

For TM modes, the fields in the dielectric layer (\( \varepsilon_2 \)) and the metallic layer (\( \varepsilon_1 \)) can be written as:
CHAPTER 2. SURFACE PLASMON POLARITON

Figure 2.1: (a) The electromagnetic field at the interface of the dielectric ($\varepsilon_2$) and metallic ($\varepsilon_1$) layers; (b) The variation of the field $E_z$ in the $z$-direction.

\[
\begin{align*}
\vec{H}_2 &= (0, H_{y2}, 0) \exp i(k_{x2}x + k_{z2}z - \omega t) \\
\vec{E}_2 &= (E_{x2}, 0, E_{z2}) \exp i(k_{x2}x + k_{z2}z - \omega t) \\
\vec{H}_1 &= (0, H_{y1}, 0) \exp i(k_{x1}x - k_{z1}z - \omega t) \\
\vec{E}_1 &= (E_{x1}, 0, E_{z1}) \exp i(k_{x1}x - k_{z1}z - \omega t)
\end{align*}
\]

Meanwhile, the field should also satisfy the Maxwell’s equations

\[
\begin{align*}
\nabla \times \vec{H}_i &= \varepsilon_i \frac{1}{c} \frac{\partial}{\partial t} \vec{E}_i \\
\nabla \times \vec{E}_i &= -\frac{1}{c} \frac{\partial}{\partial t} \vec{H}_i \\
\nabla \cdot \varepsilon_i \vec{E}_i &= 0 \\
\nabla \cdot \vec{H}_i &= 0
\end{align*}
\]

and the continuity boundary conditions $E_{x1} = E_{x2}, H_{y1} = H_{y2}$ and $\varepsilon_1 E_{z1} = \varepsilon_2 E_{z2}$. Then we can obtain the results that
2.2. OPTICAL PROPERTIES

\[ k_{x1} = k_{x2} = k_x \] \hspace{1cm} (2.4a)

\[ \frac{k_{z1}}{\varepsilon_1} + \frac{k_{z2}}{\varepsilon_2} = 0 \] \hspace{1cm} (2.4b)

\[ k_{z1}^2 + k_{z2}^2 = \varepsilon_1 \left( \frac{\omega}{c} \right)^2 \] \hspace{1cm} (2.4c)

From Eq. (2.4a) and Eq. (2.4b), we get that

\[ k_x = \frac{\omega}{c} \left( \frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2} \right)^{1/2} \] \hspace{1cm} (2.5)

For TE modes, the corresponding fields can be written as:

\[
\begin{align*}
  z > 0 & \quad \vec{H}_2 = (H_{x2}, 0, H_{z2}) \exp i(k_{x2}x + k_{z2}z - \omega t) \\
  & \quad \vec{E}_2 = (0, E_{y2}, 0) \exp i(k_{x2}x + k_{z2}z - \omega t) \\
  z < 0 & \quad \vec{H}_1 = (H_{x1}, 0, H_{z1}) \exp i(k_{x1}x - k_{z1}z - \omega t) \\
  & \quad \vec{E}_1 = (0, E_{y1}, 0) \exp i(k_{x1}x - k_{z1}z - \omega t)
\end{align*}
\] \hspace{1cm} (2.6a)

Together with the Maxwell’s equations (2.3) and the continuity boundary conditions \( H_{x1} = H_{x2}, E_{y1} = E_{y2} \) and \( H_{z1} = H_{z2} \), we get that

\[ E_{y1}(k_{z1} + k_{z2}) = 0 \] \hspace{1cm} (2.7)

As the surface waves require that \( \text{Re}[k_{z1}] > 0 \) and \( \text{Re}[k_{z2}] > 0 \), so the Eq. (2.7) is fulfilled only when \( E_{y1} = 0 \), i.e. \( E_{y1} = E_{y2} = 0 \). Similarly, we get \( H_{x1} = H_{x2} = 0 \) and \( H_{z1} = H_{z2} = 0 \), it means no surface wave can exist for TE modes.

2.2 Optical Properties

According to the Eq. (2.5) for TM modes, for the dielectric layer, it is obvious that \( \varepsilon_2 > 0 \); and for the metallic layer, \( \varepsilon_1 < 0 \). Assuming that \( |\varepsilon_1| > \varepsilon_2 \), which can be easily satisfied for a metal in the visible and near infrared range, we come to the result that \( k_x > \sqrt{\varepsilon_2 \omega}/c \). Together with the Eq. (2.4c), it is known that \( k_{z1}^2 < 0 \), which means \( k_{z1} \) is imaginary and the fields in both layers decay exponentially from the interface \( z = 0 \), as shown in Fig. 2.1(b).
Now we come back to the wave vector \( k_x \) and rewrite it in the complex form of \( k_x = k'_x + ik''_x \). Similarly, assuming that \( \varepsilon_1 = \varepsilon'_1 + i\varepsilon''_1 \) with \( \varepsilon''_1 \ll |\varepsilon'_1| \), it is deduced that

\[
\begin{align*}
    k'_x &= \frac{\omega}{c} \left( \frac{\varepsilon'_1 \varepsilon_2}{\varepsilon'_1 + \varepsilon_2} \right)^{1/2} \\
    k''_x &= \frac{\omega}{c} \left( \frac{\varepsilon'_1 \varepsilon_2}{\varepsilon'_1 + \varepsilon_2} \right)^{3/2} \frac{\varepsilon''_1}{2(\varepsilon'_1)^2}
\end{align*}
\]  

(2.8a) (2.8b)

Here \( k''_x \) determines the propagation loss primarily caused by the Ohmic energy absorption in metal. When the surface wave propagates along an interface of the dielectric and metal, the intensity will decay as a factor of \( e^{-2k''_x z} \). The propagation length at which the intensity decays to \( 1/e \) is

\[
L_p = \frac{1}{2k''_x} = \frac{c}{\omega} \left( \frac{\varepsilon'_1 + \varepsilon_2}{\varepsilon'_1 \varepsilon_2} \right)^{3/2} \frac{(\varepsilon'_1)^2}{\varepsilon''_1}
\]  

(2.9)

Consider the electromagnetic fields normal to the interface (in \( z \)-direction), the amplitude of the surface wave decays as \( e^{-|k_{zi} z|} \). Then the skin depths in the dielectric layer (\( z_2 \)) and the metallic layer (\( z_1 \)) are

\[
\begin{align*}
    z_2 &= \frac{c}{\omega} \left( \frac{\varepsilon'_1 + \varepsilon_2}{\varepsilon'_2} \right)^{1/2} \\
    z_1 &= \frac{c}{\omega} \left( \frac{\varepsilon'_1 + \varepsilon_2}{\varepsilon'_1} \right)^{1/2}
\end{align*}
\]  

(2.10a) (2.10b)

There is a trade-off between the propagation length \( L_p \) and the skin depth \( z_1 \): in the visible and infrared range, as the increase of the wavelength, the propagation length \( L_p \) increases with the skin depth \( z_1 \) decreases. It means that a better mode confinement is always followed by a smaller propagation length.

### 2.3 Plasma Model

In the previous sections, we investigate the electromagnetic properties of the surface wave initiated from Maxwell’s equations, and the optical properties are obtained by analyzing the field distribution at the interface between a dielectric layer and a metal layer. Here, we will study the properties of SPPs from the so-called plasma model [9].

For most metals, the optical properties can be described by the plasma model in the visible and infrared range. In such a model, the free electron gas has the
number density $n$ with the effective mass $m$ for each electron. Excited by the external electromagnetic field, the electrons will oscillate with a frequency $\omega$ and then damp with a frequency $\gamma = 1/\tau$, where $\tau$ is the relaxation time. At room temperature, the value of $\tau$ is $\sim 10^{-14}$s, leading to that $\gamma \approx 10^{14}$Hz [9].

The motion equation for a single electron in such a free electron gas can be written as

$$m \frac{\partial^2 \vec{x}}{\partial t^2} + m\gamma \frac{\partial \vec{x}}{\partial t} = -e \vec{E}$$

(2.11)

Assuming that the external electric field has the form $\vec{E} = \vec{E}_0 e^{-i\omega t}$, one solution of the Eq. (2.11) is

$$\vec{x}(t) = \frac{e}{m(\omega^2 + i\gamma \omega)} \vec{E}(t)$$

(2.12)

The corresponding polarization $\vec{P}(t)$ can be expressed as

$$\vec{P}(t) = -ne\vec{x}(t) = -\frac{ne^2}{m(\omega^2 + i\gamma \omega)} \vec{E}(t)$$

(2.13)

and the dielectric displacement $\vec{D}(t)$ is

$$\vec{D}(t) = \varepsilon_0 \vec{E}(t) + \vec{P}(t) = \varepsilon_0(1 - \frac{\omega_p^2}{\omega^2 + i\gamma \omega}) \vec{E}(t)$$

(2.14)

where $\omega_p = \sqrt{ne^2/\varepsilon_0 m}$ is defined as the plasma frequency. The dielectric function can be written as

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\gamma \omega}$$

(2.15)

Eq. (2.15) is known as the Drude model which we will use to calculate the dispersive permittivities of metals in this thesis. For complex $\varepsilon(\omega) = \varepsilon'(\omega) + i\varepsilon''(\omega)$, we have

$$\varepsilon'(\omega) = 1 - \frac{\omega_p^2 \tau^2}{1 + \omega^2 \tau^2}$$

(2.16a)

$$\varepsilon''(\omega) = \frac{\omega_p^2 \tau}{\omega(1 + \omega^2 \tau^2)}$$

(2.16b)
Chapter 3

Design and Simulation Methods

Since the Maxwell’ Equations established in 1873, there is a fast development of the theoretical and experimental investigations of the electromagnetic phenomena. Electromagnetic theories have been widely applied in many fields, such as wireless and fiber communication, microwave, antenna, detector, etc. In a real environment, the proposed structures are usually very complicated for which analytical solutions do not exist. To well study the properties of complex problems, numerical methods are required. Also with the development of the computer technology, more and more numerical methods are developed: Finite Element Method (FEM) [35], Method of Moment (MoM) [36], Finite-Difference Time-Domain Method (FDTD) [37], Beam Propagation Method (BPM) [38], etc. In this chapter, we will discuss the principles and applications of two popular methods: FEM and FDTD, which are the primary design and simulation methods in our study of plasmonic devices in the thesis.

3.1 Finite Element Method

Finite Element Method is probably the most popular numerical method for solving partial differential problems. The history of the FEM can be track back to 1940s, and with a continuous development of the mathematical method and the computer technology in the followed decades, it becomes an important branch of numerical methods for physics and engineering. In the FEM, the simulated domain will be partitioned into subdomains and the final result can be obtained by summarizing the results from each subdomains. This characteristic makes it superior to deal with complex structures and an accurate result can be expected with sufficiently small subdomains.

To introduce the principle of the FEM, we take a two-dimensional Poisson problem for example with the function $u(x, y)$ satisfies that
\[
\begin{align*}
-\Delta u(x, y) &= f(x, y) \quad \text{in } \Omega \\
u(x, y) &= 0 \quad \text{in } \partial \Omega
\end{align*}
\] (3.1)

where \( \Delta = \nabla^2 \) is the Laplacian, \( \Omega \) is the calculational region in the \( x - y \) plane and \( \partial \Omega \) is the boundary of the region. Here we introduce a function \( v(x, y) \) which satisfies the condition that \( v(x, y) = 0 \) at everywhere in the boundary \( \partial \Omega \). Then we get the integral equation as following:

\[
\int_{\Omega} (-\Delta u - f)v \, dxdy = \int_{\Omega} \nabla u \cdot \nabla v \, dxdy - \int_{\Omega} fv \, dxdy - \oint_{\partial \Omega} (\vec{n} \cdot \nabla u)v \, ds = 0
\] (3.2)

As \( v = 0 \) at \( \partial \Omega \), it can be deduced to be

\[
\int_{\Omega} fv \, dxdy = -\int_{\Omega} \nabla u \cdot \nabla v \, dxdy = -\phi(u, v)
\] (3.3)

which is the so-called weak form of Eq. (3.1). Now what we should do is as its name that we divide the whole region \( \Omega \) into a finite number of small elements \( \Omega_k \) as shown in Fig. 3.1

![Figure 3.1: The finite element partition of the region \( \Omega \) into small elements \( \Omega_k \).](image)

With a finer partition, the region \( \Omega \) will be more like an ellipse and the corresponding simulation result will be more accurate. Meanwhile, a finer partition requires more computer memories and time, so a proper partition is important.

Now, the function \( u(x, y) \) can be rewritten in the discretized form.
3.1. Finite Element Method

\[ u(x, y) = \sum_{k=1}^{n} u_k(x, y)v_k(x, y) \]  

(3.4)

then the Eq. (3.3) becomes

\[- \sum_{k=1}^{n} u_k \phi(v_k, v_j) = \int f v_j dx dy \]  

(3.5)

it can be expressed in a matrix form that

\[-K \vec{u} = \vec{f} \]  

(3.6)

where \( \vec{u} = (u_1, ..., u_n)^T \), \( \vec{f} = (f_1, ..., f_n)^T \) with \( f_j = \int f v_j dx dy \) and \( K = (K_{ij}) \) with \( K_{ij} = \phi(v_i, v_j) \).

Figure 3.2: (a) Schematic of the directional hybrid coupler composed of a hybrid plasmonic waveguide and a Si dielectric waveguide; (b) The field distribution \( E_y \) of the quasi-odd mode.

In the thesis, the FEM methods are widely implemented in the simulations of the eigenmodes of the waveguides. Take the directional hybrid coupler composed of a hybrid plasmonic waveguide and a Si dielectric waveguide as an example (See Fig. 3.2(a)) [39]. Using a FEM-based commercial software COMSOL Multiphysics, the field distribution of the supported modes for the coupler can be obtained, such as the so-called quasi-odd mode shown in Fig. 3.2(b). It should be noticed that, since the electromagnetic field is mainly concentrated inside the gap of the hybrid plasmonic waveguide, it is better to use a finer partition in this gap to get a more accurate result; meanwhile, to save the computer memories and time, a coarser partition can be used for the silica layer and the surrounding region.
3.2 Finite-Difference Time-Domain Method

The Finite-Difference Time-Domain Method is another very popular numerical method for electromagnetic theory, which was firstly proposed by Kane Yee in 1966. The components $\vec{E}$ and $\vec{H}$ in the electromagnetic field are related by the partial form of Maxwell’s Equations. By using a central difference approximation, Maxwell’s equations can be translated to be the discretized form both in time and space. Then each component $\vec{E}$ (or $\vec{H}$) is surrounded by four $\vec{H}$ (or $\vec{E}$) components. With an initial value, the variation of the electromagnetic field in each point can be deduced in time.

![Figure 3.3: Schematics of a Yee cell for the FDTD in Cartesian coordinate, with the distribution of the electric and magnetic field components.](image)

Different from the FEM, the FDTD can deal with electromagnetic fields within a wide range of frequencies in a single step. And with the time domain character, the FDTD can well simulate the propagation process of the electromagnetic wave inside the proposed structure which is helpful to understand the physics behind. Maxwell curl equations are

$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J} \quad (3.7a)$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} + \vec{J}_m \quad (3.7b)$$

In the isotropic materials, $\vec{D} = \varepsilon \vec{E}, \vec{B} = \mu \vec{H}, \vec{J} = \sigma \vec{E}, \vec{J}_m = \sigma_m \vec{E}$. In the FDTD
3.2. **FINITE-DIFFERENCE TIME-DOMAIN METHOD**

Simulations, the proposed structures will be discretized into the so-called Yee cells, and the three-dimensional unit is shown in Fig. 3.3.

With a central difference approximation, Maxwell curl equations can be rewritten in the discretized form:

\[
E_{x}^{n+1}(i + \frac{1}{2}, j, k) = A(m) \cdot E_{x}^{n}(i + \frac{1}{2}, j, k)
+ B(m) \cdot \left[ \frac{H_{z}^{n+1/2}(i + \frac{1}{2}, j + \frac{1}{2}, k) - H_{z}^{n+1/2}(i + \frac{1}{2}, j - \frac{1}{2}, k)}{\Delta y} - \frac{H_{y}^{n+1/2}(i + \frac{1}{2}, j, k + \frac{1}{2}) - H_{y}^{n+1/2}(i + \frac{1}{2}, j, k - \frac{1}{2})}{\Delta z} \right]
\]  

\[
E_{y}^{n+1}(i, j + \frac{1}{2}, k) = A(m) \cdot E_{y}^{n}(i, j + \frac{1}{2}, k)
+ B(m) \cdot \left[ \frac{H_{z}^{n+1/2}(i, j + \frac{1}{2}, k + \frac{1}{2}) - H_{z}^{n+1/2}(i, j - \frac{1}{2}, k + \frac{1}{2})}{\Delta z} - \frac{H_{z}^{n+1/2}(i + \frac{1}{2}, j + \frac{1}{2}, k) - H_{z}^{n+1/2}(i + \frac{1}{2}, j - \frac{1}{2}, k)}{\Delta x} \right]
\]  

\[
E_{z}^{n+1}(i, j, k + \frac{1}{2}) = A(m) \cdot E_{z}^{n}(i, j, k + \frac{1}{2})
+ B(m) \cdot \left[ \frac{H_{z}^{n+1/2}(i + \frac{1}{2}, j + \frac{1}{2}, k) - H_{z}^{n+1/2}(i - \frac{1}{2}, j, k + \frac{1}{2})}{\Delta x} - \frac{H_{y}^{n+1/2}(i, j, k + \frac{1}{2}) - H_{y}^{n+1/2}(i, j, k - \frac{1}{2})}{\Delta y} \right]
\]  

where \(i, j, k\) and \(m\) are the coordinates of \(E_{x}^{n+1}(x, y, z)\); \(\Delta x, \Delta y\) and \(\Delta z\) are the spatial increments between two neighbor points and they stand for the fineness of the Yee cell; and

\[
A(m) = \frac{\varepsilon(m) - \sigma(m) \Delta t/2}{\varepsilon(m) + \sigma(m) \Delta t/2}
\]  

\[
B(m) = \frac{\Delta t}{\varepsilon(m) + \sigma(m) \Delta t/2}
\]  

Meanwhile,
\( H_{n+1/2}^{x}(i, j + \frac{1}{2}, k + \frac{1}{2}) = C(m) \cdot H_{n}^{x}(i, j + \frac{1}{2}, k + \frac{1}{2}) \)
\[- D(m) \cdot \left[ \frac{E_{z}^{n}(i, j + 1, k + \frac{1}{2}) - E_{z}^{n}(i, j, k + \frac{1}{2})}{\Delta z} \right] \]
\[- \frac{E_{y}^{n}(i, j, k + 1) - E_{y}^{n}(i, j + \frac{1}{2}, k)}{\Delta z} \] (3.10a)

\( H_{n+1/2}^{y}(i + \frac{1}{2}, j + \frac{1}{2}, k) = C(m) \cdot H_{n}^{y}(i + \frac{1}{2}, j + \frac{1}{2}, k) \)
\[- D(m) \cdot \left[ \frac{E_{z}^{n}(i + \frac{1}{2}, j + 1, k) - E_{z}^{n}(i, j + \frac{1}{2}, k)}{\Delta x} \right] \]
\[- \frac{E_{x}^{n}(i + \frac{1}{2}, j + 1, k) - E_{x}^{n}(i + \frac{1}{2}, j, k)}{\Delta y} \] (3.10b)

\( H_{n+1/2}^{z}(i + \frac{1}{2}, j, k + \frac{1}{2}) = C(m) \cdot H_{n}^{z}(i + \frac{1}{2}, j, k + \frac{1}{2}) \)
\[- D(m) \cdot \left[ \frac{E_{z}^{n}(i + 1, j + 1, k) - E_{z}^{n}(i + 1, j, k)}{\Delta x} \right] \]
\[- \frac{E_{y}^{n}(i + \frac{1}{2}, j + 1, k) - E_{y}^{n}(i + \frac{1}{2}, j, k + \frac{1}{2})}{\Delta y} \] (3.10c)

where

\[ C(m) = \frac{\mu(m) - \sigma_{m}(m) \Delta t/2}{\mu(m) + \sigma_{m}(m) \Delta t/2} \] (3.11a)

\[ D(m) = \frac{\Delta t}{\mu(m) + \sigma_{m}(m) \Delta t/2} \] (3.11b)

For higher fineness (smaller \( \Delta x, \Delta y, \Delta z \)), the simulation results are much more accurate. However, high fineness requires large memory and long calculation time, so in the real simulation process, we will choose a proper fineness to make sure the spatial increment smaller than \( \lambda/8 \). On the other hand, the stability [40] of the FDTD requires a so-called Courant condition that

\[ c \Delta t \leq \frac{1}{\sqrt{\left(\frac{1}{\Delta x}\right)^2 + \left(\frac{1}{\Delta y}\right)^2 + \left(\frac{1}{\Delta z}\right)^2}} \] (3.12)

In the simulations, the computational domain is finite. When the electromagnetic waves propagate to the boundaries, they will have reflection or scattering, which
3.2. **FINITE-DIFFERENCE TIME-DOMAIN METHOD**

will influence the simulation results. Then an absorbing boundary condition should be set, and in the FDTD we use the perfect matched layer (PML) method. In the PML, the conductivity keeps increasing from the inner to the outer according to the followed equation

\[
\sigma(\rho) = \sigma_{max}\left(\frac{\rho}{d}\right)^n \quad n = 1, 2
\]

(3.13)

where \(d\) is the thickness of the PML, and \(\rho\) is the position in the PML where \(\rho = 0\) at the inner boundary and \(\rho = d\) at the outer boundary. For \(n = 1\), \(\sigma\) has a linear variation; and for \(n = 1\), \(\sigma\) has a parabolic variation. Usually \(n = 2\) is chosen for the FDTD and the reflection coefficient is expressed as [41]

\[
R(\theta) = \exp\left(-\frac{2\cos\theta}{\varepsilon_0c} \int_0^\rho \sigma(\rho')d\rho'\right)
\]

(3.14)

where \(\theta\) is the incident angle of the electromagnetic wave. When \(\theta = 0\), \(R(0)\) is the reflection coefficient for the normal incidence.

Figure 3.4: (a) Schematic diagram for the direct coupling; (b) \(E_y\) field distributions for the direct coupling between a silicon waveguide with a width \(w_{Si} = 450\text{nm}\) and a hybrid plasmonic waveguide with a width \(w_{plas} = 200\text{nm}\).

Fig. 3.4 shows the \(E_y\) field distributions of a directly connecting between a silicon-on-insulator (SOI) waveguide and a HP waveguide [42], which is obtained by a home-made FDTD program. It clearly depicts the variation of the field as it propagates from the SOI waveguide to the HP waveguide.
Chapter 4

Coupler and Splitter between Dielectric Waveguide and Plasmonic Waveguide

Plasmonic waveguides are expected to be candidates for the next-generation integrated nanophotonic circuit system, with the capability of guiding light in sub-wavelength scale. Recently, many different types of plasmonic waveguides have been studied, such as metallic nanoparticle chain waveguides, metallic wire or stripe waveguides, channel or wedge plasmonic waveguides, plasmonic slot waveguides, hybrid plasmonic waveguides, etc. Generally, there is a trade-off for these plasmonic waveguides between their mode confinement and propagation length. Among them, the hybrid plasmonic waveguide is relatively superior, since it has a relatively large propagation length with a subwavelength mode confinement simultaneously. That is the reason why we have paid much attention to this structure. However, compared to those of conventional dielectric waveguides, the propagation length of a hybrid plasmonic waveguide is still far too short.

As a probable solution, a hybrid integrated system of plasmonic and dielectric waveguides can be proposed as a compromise between the compactness and low loss: plasmonic waveguides are implemented as miniaturized devices, while dielectric waveguides are used for delivering optical signals over a relatively long distance. For this system, efficient coupling between a dielectric waveguide and a plasmonic waveguide is an important problem to be considered carefully.

In this chapter, we will discuss the coupling between a silicon-on-insulator waveguide and a hybrid plasmonic waveguide by a HP linear taper coupler. And for the splitting from a SOI waveguide to several HP waveguides, a HP multimode interference based power splitter will be investigated.
CHAPTER 4. COUPLER AND SPLITTER BETWEEN DIELECTRIC WAVEGUIDE AND PLASMONIC WAVEGUIDE

4.1 Broadband Coupler between Silicon Waveguide and Hybrid Plasmonic Waveguide

4.1.1 Silicon and Hybrid Plasmonic Waveguides

Figure 4.1: (a) The cross-section of a SOI waveguide with the width $w_{Si}$ and height $h_{Si}$; (b) The field $E_y$ of the fundamental TM mode for the same SOI waveguide; (c) The cross-section of a HP waveguide composed by depositing an alumina layer ($h_{Al_2O_3}$) and then a silver layer ($h_{Ag}$) on top of a SOI waveguide; (d) The field $E_y$ of the fundamental TM mode for a HP waveguide with the width $w_{Si} = 450 \text{nm}$ and $h_{Si} = 250 \text{nm}$, $h_{Al_2O_3} = 50 \text{nm}$, $h_{Ag} = 100 \text{nm}$.

The silicon waveguide proposed here is a standard SOI waveguide (See Fig. 4.1(a)) with a height $h_{Si} = 250 \text{nm}$ and a width $w_{Si} = 450 \text{nm}$. Only the fundamental TE and TM modes (See Fig. 4.1(b)) are supported at the telecommunication wavelength $\lambda = 1550 \text{nm}$ for the SOI waveguide. The hybrid plasmonic waveguide can be obtained by depositing an alumina layer with $h_{Al_2O_3} = 50 \text{nm}$ and then a silver layer with $h_{Ag} = 100 \text{nm}$ on top of a SOI waveguide (See Fig. 4.1(c)). With the width $w_{plas}$ smaller than 240nm, only a fundamental TM mode exists in the HP waveguide. In Fig. 4.1(d) shows the $E_y$ mode field of the HP waveguide.
4.1. BROADBAND COUPLER BETWEEN SILICON WAVEGUIDE AND HYBRID PLASMONIC WAVEGUIDE

with \( w_{\text{plas}} = 200\text{nm} \). All the modes here can be easily obtained by the FEM based commercial software COMSOL Multiphysics with the parameters set to be \( n_{\text{Si}} = 3.45 \), \( n_{\text{SiO}_2} = 1.45 \), \( n_{\text{Al}_2\text{O}_3} = 1.74 \), and the dispersive permittivity \( \varepsilon_{\text{Ag}} \) is calculated by a Drude model fitted with the experiment data [43].

4.1.2 Direct Coupling

Compared with the SOI waveguide, there is a distinct difference of the field distribution for the HP waveguide that the electric field is largely concentrated within the 50nm alumina layer. So by directly connecting these two waveguides together, a large coupling loss can be expected. To deeply investigate the coupling properties, a three dimensional FDTD method is used to simulate the light coupling performance. Material parameters are the same as those used in the FEM simulations. The fundamental TM mode of the silicon waveguide is excited by a Gaussian source with a central wavelength of 1550nm, at which \( \varepsilon_{\text{Ag}} = -87 - 8.7i \).

![Figure 4.2](image-url)

**Figure 4.2:** (a) The coupling efficiency shown as a function of the HP waveguide width (red solid line), compared with the proportion of power flow in the central section of the silicon waveguide with the same width (blue dashed line); (b) The coupling efficiency shown as a function of the height of the alumina layer.

In this condition, the coupling loss is mainly caused by two factors: the interface reflection and the mismatch between the two modes. The FDTD simulations reveal that the interface reflection for such a direct coupling is less than 4%. Thus the radiation loss caused by the mode mismatch dominates the total coupling loss. It can be expected that, with the decrease of \( w_{\text{plas}} \), the coupling efficiency \( \eta \) will decrease due to the increase of the mode mismatch. Fig. 4.2(a) shows the dependence of the coupling efficiency at \( \lambda = 1550\text{nm} \) from the SOI waveguide to the HP waveguide on the width of the HP waveguide. At \( w_{\text{plas}} = 450\text{nm} \), the coupling efficiency is \( \eta = 85\% \) (0.7dB); and \( \eta \) will rapidly decrease to 45\% (3.4dB) as the width decreases to be \( w_{\text{plas}} = 100\text{nm} \). As a comparison, the portion of the power in the central section of the silicon waveguide, corresponding to the area of the
CHAPTER 4. COUPLER AND SPLITTER BETWEEN DIELECTRIC WAVEGUIDE AND PLASMONIC WAVEGUIDE

HP waveguide, is also depicted in Fig. 4.2(a). The power portion in the central section of the SOI waveguide is found only comparable to the coupling efficiency between the SOI and the HP waveguide when the HP waveguide width is larger than 250nm. For a narrow HP waveguide with $w_{\text{plas}} < 250\text{nm}$, the coupling efficiency is larger than the portion of the power flowing in the central section of the SOI waveguide. This means that a narrow HP waveguide can collect light from a dielectric waveguide with a much larger cross-sectional area. However, in order to obtain a higher coupling efficiency, especially for a HP waveguide with a very narrow width, direct coupling is certainly not sufficient. More specifically, for a HP waveguide with $w_{\text{plas}} = 200\text{nm}$, the coupling efficiency is only $\eta = 60\%$ (2.2dB).

For HP waveguide, as the increase of the height of the alumina layer $h_{\text{Al}_2\text{O}_3}$, more electromagnetic energy will exist in the silicon layer, which obviously will influence the coupling efficiency. In Fig. 4.2(b) we show the dependence of the direct coupling efficiency $\eta$ on the $h_{\text{Al}_2\text{O}_3}$ for HP waveguides with fixed width $w_{\text{plas}} = 200\text{nm}$. As the alumina layer becomes larger, the coupling efficiency also becomes higher, because a thicker alumina layer reduces the mode mismatch between the two different kinds of waveguides and therefore increases the coupling efficiency. However the increase in efficiency is not significant: when the height of the alumina layer $h_{\text{Al}_2\text{O}_3}$ increases from 10nm to 100nm, the coupling efficiency $\eta$ increases from 53\% to 63\%. To ensure a relatively good mode field confinement together with a relatively long propagation length, $h_{\text{Al}_2\text{O}_3} = 50\text{nm}$ is a good choice.

### 4.1.3 Hybrid Plasmonic Linear Taper Coupler

To increase the coupling efficiency, several methods have been proposed both theoretically and experimentally [24, 44–51], such as multisection taper, linear taper, etc. Here, we introduce a hybrid plasmonic linear taper to improve the coupling efficiency between a silicon waveguide ($w_{\text{Si}} = 450\text{nm}$) and a HP waveguide with $w_{\text{plas}} = 200\text{nm}$, $h_{\text{Al}_2\text{O}_3} = 50\text{nm}$ (See Fig. 4.3(a)). The HP taper has the same structure as the HP waveguide in the vertical direction with the width decreases linearly from 450nm to 200nm. A linear taper reduces the abrupt change in geometry and partially in material parameters, and it is therefore expected to reduce the radiation loss. For a linear HP taper, the taper slope is vital for coupling efficiency: a sufficiently long taper can be expected to reduce the radiation loss to the minimum, and a coupling efficiency of almost $85\%$ can be expected which is as high as the direct coupling with a 450nm HP waveguide. However, on the other hand, the propagation loss has to considered which is an inherent property for any plasmonic waveguide. The existence of propagation loss certainly obstructs the deployment of a very long HP taper. It is one of our objectives in this paper to optimize the taper length for achieving the highest coupling efficiency between two waveguides.

Also from 3D-FDTD simulations, we obtain the dependence of the coupling efficiency on the taper length $L_{\text{taper}}$ at the wavelength $\lambda = 1550\text{nm}$, as shown in Fig.
4.1. BROADBAND COUPLER BETWEEN SILICON WAVEGUIDE AND HYBRID PLASMONIC WAVEGUIDE

Figure 4.3: (a) Schematic diagram for the HP linear taper coupler. (b) $E_y$ distribution at the center plane of the alumina layer for the coupling with a 0.4$\mu$m-long HP taper. (c) The dependence of the coupling efficiency on the length of the HP taper (red solid line), compared with the same design with lossless silver (blue dashed line). The inset shows the corresponding propagation loss for the HP taper.

4.3(c) (red solid line). When the taper length $L_{taper}$ increases from 0 to 0.4$\mu$m, the coupling efficiency $\eta$ increases from 60\% (2.2dB) to 70\% (1.5dB). This reflects that the coupling efficiency can be improved significantly with even a very short HP taper. When the taper length further increases, the propagation loss becomes larger and begin to diminish the total coupling efficiency. Indeed, ignoring the slight oscillation caused by the Fabry-Perot effect of the HP taper, $\eta$ keeps decreasing as $L_{taper}$ increases from 0.4 to 3$\mu$m. For a taper with $L_{taper} = 3\mu$m, the coupling efficiency is only $\eta = 58\%$ (2.3dB), even lower than the direct coupling. Hence, it is better to limit the taper length $L_{taper}$ to be smaller than 2.5$\mu$m.

As we know, the coupling loss is dominated by two kinds of losses: the radiation loss and the propagation loss. From 3D-FDTD simulations, it is known that the interface reflection for the HP taper are less than 2\% in energy loss which can be safely neglected. In our previous discussions, the trade-off between the radiation and propagation losses was roughly studied. To understand the contribution of each factor more clearly, we further carry out 3D-FDTD calculations for the same structures with lossless silver. The corresponding coupling efficiency $\eta$ at $\lambda = 1550nm$ is also shown in Fig. 4.3(c) (blue dashed line). With lossless silver, the energy loss in the coupling is only due to the radiation loss. From Fig. 4.3(c),
also ignoring the slight oscillations in the curve, we see that as the taper length increases from 0 to 3µm, the coupling efficiency keeps increasing to be almost 72% (1.4dB). For a large taper length (> 0.4µm), the reduction of the radiation loss with the increase of the taper length is not so obvious compared with shorter tapers. Comparing the coupling efficiency with the coupling efficiency with lossy silver, the propagation loss for the HP taper is obtained, shown in the inset of Fig. 4.3. There is an almost linear increase of the propagation loss with the increase of the taper length. At a taper length of 3µm, the propagation loss is even as large as 0.9dB which can well explain the so low coupling efficiency. For a 0.4µm-long HP taper (Fig. 4.3(b)), the very low propagation loss (0.1dB) and relatively low radiation loss (1.4dB) make it the optimal coupler in practical with the highest coupling efficiency.

Figure 4.4: Coupling efficiency in the wavelength range (1450, 1650)nm, for the direct coupling (blue dashed line), the 0.4µm-long HP taper coupler (red solid line) and the 0.4µm-long silicon taper coupler (black dash-dotted line).

Since a linear taper coupler is without relying on any resonance mechanism, a broadband enhancement in coupling efficiency can be expected. In Fig. 4.4, we show the coupling efficiency of the optimal 0.4µm-long HP taper coupler over a broadband wavelength range of 1450 ~ 1650nm. Compared with the direct coupling, a 0.5 ~ 0.7dB improvement in coupling efficiency is obtained. For a further comparison, the coupler composed by a 0.4µm-long silicon linear taper, which has the similar structure as the HP taper but without the alumina and silver layers, is also examined by 3D-FDTD simulations. A rather low coupling efficiency is obtained in the whole wavelength range which is only η = 41% (3.9dB) at the wavelength λ = 1550nm (See Fig. 4.4, the black dash-dotted line). It is caused by the drastic mode mismatch between a 200nm-wide SOI waveguide and a 200nm-wide HP
4.2 COUPLING BETWEEN SILICON AND HYBRID PLASMONIC WAVEGUIDES BY MULTIMODE INTERFERENCE POWER SPLITTER

waveguide.

4.1.4 Experimental Results

Figure 4.5: SEM images of the fabricated devices (top view), (a) The image of the whole system; (b) The amplified image of the coupler; (c) Normalized transmission spectrum of the coupler.

Fig. 4.5(a) and (b) are the scanning electron microscope images of the top view of a fabricated HP waveguide and a HP coupler. The plasmonic tapered coupler has a width \( w_{\text{taper}} = 240 \text{ nm} \) from silicon waveguide down to \( w_{\text{plas}} = 185 \text{ nm} \) to the HP waveguide. The tapered couplers have a length \( L_{\text{taper}} = 1.5 \mu\text{m} \) and the HP waveguide has a length \( L_{\text{plas}} = 2 \mu\text{m} \).

The silicon waveguide and the underlying silicon layer of the plasmonic coupler and the HP waveguide are fabricated first by the electron beam lithography (EBL) and the inductively coupled plasmon (ICP) etching. Due to the deviation in the EBL process, the final widths of the silicon waveguide and the silicon layer of the HP waveguide are a little bit different from the original design. So a 3D-FDTD simulation is performed with the modified parameters to compare with the experimental result (See Fig. 4.5(c)). The transmission spectrum of the device is normalized by the output power of an identical silicon waveguide without the top metallic layer. The measured transmission spectrum is in good agreement with the FDTD calculations by ignoring the regular oscillation in the experimental spectrum.

4.2 Coupling between Silicon and Hybrid Plasmonic Waveguides by Multimode Interference Power Splitter

In the previous section, we discussed the coupling between a single silicon waveguide and a single hybrid plasmonic waveguide by a HP linear taper. In practical applications, there will be a requirement to split power form one dielectric wave-
CHAPTER 4. COUPLER AND SPLITTER BETWEEN DIELECTRIC WAVEGUIDE AND PLASMONIC WAVEGUIDE

Guide to several HP waveguides, with a controllable splitting ratio. In this case, a multimode interference [52–58] based power splitter will be a good choice.

4.2.1 Self-imaging Principle

MMI power splitter relies on the self-imaging principle that the input electromagnetic field profile is reproduced as multiple-fold images at certain propagation distances. At the entrance of the MMI regime, the input filed $\Phi(0)$ can be decomposed into all guided modes $\phi_{\nu}(0)$ that can be supported by the multimode waveguide.

$$\Phi(0) = \sum_{\nu=0}^{m-1} a_{\nu} \phi_{\nu}(0)$$  \hspace{1cm} (4.1)

where $a_{\nu}$ is the modal amplitude and $\nu$ is the mode number. At the distance $z = L$, the field has the form

$$\Phi(L) \approx \sum_{\nu=0}^{m-1} a_{\nu} \phi_{\nu}(0) \exp \left( \frac{i\nu(\nu + 2)\pi}{3L_{\pi}} L \right)$$  \hspace{1cm} (4.2)

where $L_{\pi} = \pi/(\beta_0 - \beta_1)$ is the beating length of the two lowest order modes, and $\beta_0 = n_0 k_0$, $\beta_1 = n_1 k_0$ are propagation constants of the two modes. Then $\Phi(L)$ will be a single image of $\Phi(0)$ at the distances of $L = p(3L_{\pi}) (p = 1, 2, 3, \ldots)$ where

$$\exp \left( \frac{i\nu(\nu + 2)\pi}{3L_{\pi}} L \right) = 1 \text{ or } (-1)^{\nu}, \text{ and the corresponding } N\text{-fold images will occur at the distances of } L = p(3L_{\pi})/N \text { [19]. If the input waveguide is connected to the center of the multimode waveguide, only even modes } (\nu = 0, 2, 4, \ldots) \text{ can be excited. According to the Eq. (4.2), } N\text{-fold images are expected to be formed at much shorter distances.}

$$L = \frac{p}{N} \left( \frac{3L_{\pi}}{4} \right) = \frac{p}{N} \frac{3\pi}{8} \frac{1}{(n_0 - n_1)}$$  \hspace{1cm} (4.3)

The reduction in the length of MMI regime will directly lead to a smaller loss owing to Ohmic absorption in our proposed plasmonic waveguide system. Due to this factor, such a central in-coupling configuration are used in all MMI structures designed in this thesis.

For a MMI, imaging resolution is an important parameter which refers to the accuracy of the reproduction of the input field. To obtain a $1 \times N$ power splitting with high imaging resolution, the designed multimode waveguide is required to support at least $N + 1$ modes.
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4.2.2 SOI-HP MMI Power Splitters

Figure 4.6: Schematics of the $1 \times 3$ SOI-HP MMI power splitter. The HP MMI regime has a width $w_{MMI}$ and a length $L_{MMI}$. The input SOI waveguide has a width $w_{\text{input}}$. The output HP waveguides have the width $w_{\text{output}}$ and the separation between them is $s$.

A schematics of the designed SOI-HP MMI power splitter is shown in Fig. 4.6. The input waveguide is a standard SOI waveguide (See Fig. 4.1(a)) with ($h_{\text{Si}} = 250\,\text{nm}$ and $w_{\text{Si}} = 450\,\text{nm}$). The MMI regime and the output waveguides are based on HP waveguide system (See Fig. 4.1(c)). Here, the software COMSOL Multiphysics is also used to simulate the complex effective indices, propagation lengths and transverse field profiles for the HP waveguide for various widths, that constitutes our proposed MMI power splitters. Since the intended operating wavelength is around the telecommunication wavelength $\lambda = 1550\,\text{nm}$, the parameters of the materials are set to be the same as that in the section 4.2.1.

For the proposed HP waveguides, there are two different types of modes existing: TE and TM modes. Since only a fundamental TM mode can be supported in a $200\,\text{nm}$-width HP waveguide, to use it as the output waveguide, we naturally focus on TM modes. The dependences of the effective indices and propagation lengths for all supported TM modes on the widths of HP waveguides at $\lambda = 1550\,\text{nm}$ are shown in Fig. 4.7(a) and (b). The fundamental $TM_{00}$ mode always exists for any width, and high-order modes will emerge as the width increases. The cut-off widths for $TM_{01}, TM_{02}$ and $TM_{03}$ modes are 450, 750 and $1100\,\text{nm}$. Hence, the widths of HP MMI regime for the proposed $1 \times 2$ and $1 \times 3$ HP MMI power splitters should be larger than 750 and $1100\,\text{nm}$ respectively, to realize high imaging resolution.
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Figure 4.7: (a) The dependence of the real part of the effective index for $TM_{00} \sim TM_{03}$ modes on the width of the HP waveguides; (b) The dependence of the propagation length for $TM_{00} \sim TM_{03}$ modes on the width of the HP waveguide. (c) The cross-section of the electric field $|E_y|$ for the $TM_{00}$ mode of a 200nm-wide HP waveguide and the $TM_{00}, TM_{01}, TM_{02}$ modes for a 1200nm-wide HP waveguide.

To observe the modes more clearly, the normalized $|E_y|$ field distributions for the supported TM modes by a 200nm-wide and a 1200nm-wide HP waveguides are shown in Fig. 4.7(c). The field distributions of all these modes are similar with the electromagnetic energy well confined in the sub-wavelength scaled alumina layer.

For the $1 \times 3$ SOI-HP MMI power splitter, the width of the MMI regime is set to be $w_{MMI} = 1200\text{nm}$. According to the self-imaging principle, it can be expected that the 1-fold, 2-fold and 3-fold images occur at the distances $L_1 = 3360\text{nm}$, $L_2 = 1680\text{nm}$ and $L_3 = 1120\text{nm}$. To confirm and optimize the power splitter, the 3D-
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Figure 4.8: (a) The $E_y$ field distribution in the center plane of the alumina layer for a $1 \times 3$ SOI-HP MMI power splitter. (b) The dependence of total transmission $\eta$ on the length of the MMI regime $L_{MMI}$ (red solid line), compared with the same structure but with lossless silver (blue dashed line). (c) The dependence of splitting ratio $\gamma$ on the length of the MMI regime $L_{MMI}$ (red solid line), compared with the same structure but with lossless silver (blue dashed line).

FDTD method is implemented to simulate the wave propagation in the system. The parameters of the materials are the same as those in the FEM simulations and the TM mode of the input SOI waveguide is excited by a Gaussian source with a central wavelength $\lambda_0 = 1550\text{nm}$. Fig. 4.8(a) shows the field distribution of $E_y$ in the center of the alumina layer for the designed 1200nm-long $1 \times 3$ SOI-HP MMI power splitter with the separation of $s = 400\text{nm}$ between the adjacent output HP waveguides. From Fig. 4.8(a), it is noticed that the electric field in the central output waveguide decays quickly compared to two side output waveguides. This is mainly caused by the strong crosstalk between the output waveguides, which can be solved by increasing their separations or adding S-bends to the two side output waveguides. Here, for the numerical simplicity, we set the power detectors in the
CHAPTER 4. COUPLER AND SPLITTER BETWEEN DIELECTRIC WAVEGUIDE AND PLASMONIC WAVEGUIDE

output waveguides at only 50nm from the interface of the MMI regime, where the influence of the crosstalk can be neglected.

To characterize the performance of a MMI power splitter, the total transmission efficiency $\eta$ and the power splitting ratio $\gamma$ [58] among the output waveguides are two important parameters. We define the transmission efficiency as $\eta = P_{\text{out}} / P_{\text{in}}$, where $P_{\text{out}}$ is the power in the output HP waveguide, and $P_{\text{in}}$ is the power in the input SOI waveguide; more specifically, $\gamma$ is defined as the ratio between the power in the central output waveguide and the average power in the two side output waveguides [24]. The dependence of $\eta$ and $\gamma$ on the MMI length $L_{\text{MMI}}$ are plotted in Fig. 4.8(b) and (c). As shown in Fig. 4.8(c) (red-solid line), the splitting ratio $\gamma$ is very sensitive to $L_{\text{MMI}}$. As $L_{\text{MMI}}$ increases from 1100 to 1300nm, $\gamma$ decreases from 1.45 to 0.64 which means more power is transmitted to the side waveguides. To realize a balanced power splitting (1:1:1), the length of the MMI regime should be $L_{\text{MMI}} = 1200$nm, where the total transmission is $\eta = 76.1\%$. There is a little bit difference between the numerical simulated and theoretical predicted on $L_{\text{MMI}}$ which is probably caused by the mode mismatch between the SOI waveguide and the HP waveguide. As a comparison, the total transmission $\eta$ and the splitting ratio $\gamma$ for the same structure but with a lossless silver layer are also shown in Fig. 4.8(b) and (c) (blue-dashed lines) where the attenuation is only due to the insertion loss [19]. The total transmission $\eta = 81.0\%$ is achieved at $L_{\text{MMI}} = 1200$nm. Comparing with the lossy silver case, the $\gamma$ curve is almost the same, which means the propagation loss influences equally to all the output waveguides. To further reduce the insertion loss, One choice is to adopt HP tapers at the output interface of the MMI regime. Unfortunately it will increase the propagation loss and in turn reduce the total transmission.

Figure 4.9: (a) The $E_y$ field distribution in the center of the alumina layer for a $1 \times 2$ SOI-HP MMI power splitter; b) The dependence of total transmission $\eta$ on the length of the MMI regime $L_{\text{MMI}}$ (red solid line), compared with the same structure but with lossless silver (blue dashed line).
4.2. COUPLING BETWEEN SILICON AND HYBRID PLASMONIC WAVEGUIDES BY MULTIMODE INTERFERENCE POWER SPLITTER

For a $1 \times 2$ SOI-HP MMI power splitter, we set the width of the MMI regime to be $w_{MMI} = 800\,\text{nm}$ for which the 2-fold image is expected to occur at the distance $L_2 = 847\,\text{nm}$ by Eq. (4.3). The corresponding field distribution of $E_y$ and the dependence of the total transmission $\eta$ on the length of the MMI regime $L_{MMI}$ are plotted in Fig. 4.9. With $L_{MMI} = 820\,\text{nm}$, the highest total transmission is achieved with $\eta = 78.3\%$ (Fig. 4.9(b), red-solid line) which is also higher than the designs with HP tapers. With a lossless silver layer, the total transmission with $L_{MMI} = 820\,\text{nm}$ increases to $82.1\%$. There is also a little bit difference between the FDTD simulated and the theoretical predicted of $L_{MMI}$ which is similar as the $1 \times 3$ SOI-HP MMI power splitter.

![Figure 4.9: The total transmission $\eta$ in the wavelength range $1500 \sim 1600\,\text{nm}$ for a $1 \times 2$ SOI-HP MMI power splitter with $w_{MMI} = 800\,\text{nm}, L_{MMI} = 820\,\text{nm}$.](image)

(b) The total transmission $\eta$ and the splitting ratio $\gamma$ in the wavelength range $1500 \sim 1600\,\text{nm}$ for a $1 \times 3$ SOI-HP MMI power splitter with $w_{MMI} = 1200\,\text{nm}, L_{MMI} = 1200\,\text{nm}$.

Due to the equation Eq. (4.3), the position for the $N$-fold image is sensitive to the wavelength, and so is the performance of the whole device. To gain quantitative knowledge about the influence of the wavelength, we simulate the variation of the total transmission $\eta$ and the splitting ratio $\gamma$ in the wavelength range of $1500 \sim 1600\,\text{nm}$ for the $1 \times 2$ ($w_{MMI} = 800\,\text{nm}, L_{MMI} = 820\,\text{nm}$) and the $1 \times 3$ ($w_{MMI} = 1200\,\text{nm}, L_{MMI} = 1200\,\text{nm}$) SOI-HP MMI power splitters. The results are plotted in Fig. 4.10. Notice that for any $1 \times 2$ SOI-HP MMI power splitter, $\gamma$ is always 1. From Fig. 4.10, the total transmission of both splitters decreases slowly but always remains higher than $70\%$ as the wavelength increases from $1500\,\text{nm}$ to $1600\,\text{nm}$. For the $1 \times 3$ HP MMI power splitter, $\gamma$ varies sharply. To limit the imbalance of the power splitting to be smaller than $10\%$, i.e. $0.9 \leq \gamma \leq 1.1$, the wavelength have to be in the range of $1543 \sim 1555\,\text{nm}$. 

![Figure 4.10: The total transmission $\eta$ in the wavelength range $1500 \sim 1600\,\text{nm}$ for a $1 \times 2$ SOI-HP MMI power splitter with $w_{MMI} = 800\,\text{nm}, L_{MMI} = 820\,\text{nm}$.](image)
4.2.3 Effect of Possible Misalignment in Fabrication

In section 4.2.2, we have theoretically studied the performance of SOI-HP MMI power splitters, and obtained the optimized parameters for $1 \times 2$ and $1 \times 3$ configurations. However, some errors are unavoidable during fabrication which may lead to deviations from the original design. As shown in Fig. 4.6, the input and output waveguides are placed in positions symmetric to the $y-z$ plane to realize a balanced splitting. If there exists some misalignments of the input and output waveguides from the designed positions during the fabrication procedure, the balanced power splitting will be broken. If a shift only occurs for the input waveguide, the imbalance of the power splitting is mainly caused by the appearance of odd modes according to Eq. (4.2). If such a shift occurs only for the output waveguides, the imbalance is mainly caused by the mode mismatch. In fabrications, the amplitude of misalignment is limited by the resolution of the fabrication procedure, which, e.g. for the electron-beam lithography and lift-off procedure, is smaller than 50 nm.

Figure 4.11: The dependences of the transmissions on the shift of the access waveguides in $x$-direction, (a) The total transmission (solid line) and the transmissions of the top (dashed line), center (dash-dotted line) and bottom (dotted line) output waveguides for a $1 \times 3$ SOI-HP MMI power splitter ($w_{MMI} = 1200 \text{nm}, L_{MMI} = 1200 \text{nm}$) with the shift of the input (blue line) and output (red line) waveguides. (b) The total transmission (solid line) and the transmissions of the top (dashed line) and bottom (dotted line) output waveguides for a $1 \times 2$ SOI-HP MMI power splitter ($w_{MMI} = 800 \text{nm}, L_{MMI} = 820 \text{nm}$) with the shift of the input (blue line) and output (red line) waveguides.

Fig. 4.11(a) shows the dependences of the transmission on the shifts of the waveguides for a $1 \times 3$ SOI-HP MMI power splitter with $w_{MMI} = 1200 \text{nm}, L_{MMI} = 1200 \text{nm}$. The total transmission and the transmission to the center output waveguide are almost unchanged, whether the shift happens for the input waveguide or the output waveguides; however, the transmission to the side output waveguides will be subject to a linear increase or decrease with the shift. As the shift increases from 0
to 50nm, the transmissions of three output waveguides will change from a balanced splitting of 25.4% : 25.3% : 25.4% (in total 76.1%) to be 28.8% : 25.6% : 21.7% (in total 76.1%) in the case that the shift is for the input waveguide, compared with 29.5% : 25.3% : 20.7% (in total 75.5%) for the shift of the output waveguides. Hence, in terms of total transmission, the influence of a shift due to misalignment is not significant, while a misalignment does adversely affect a balanced splitting.

The dependences of the transmission on the waveguide shifts for a 1 × 2 SOI-HP MMI power splitter with \( w_{MMI} = 800\, nm, L_{MMI} = 820\, nm \) is shown in Fig. 4.11(b). As the shift increases from 0 to 50nm, the transmissions of two output waveguides change from a balanced splitting of 39.2% : 39.2% (in total 78.3%) to 44.5% : 33.8% (in total 78.3%) in the case that the shift occurs for the input waveguide, compared to 40.2% : 36.7% (in total 76.9%) for the shift occurs of the output waveguides. It is noticed that the influence of a shift on the input waveguide is more serious than that on the output waveguides. Therefore more attention should be paid in the fabrication procedure to reduce the shift of the input waveguide in order to realize a balanced power splitting.
Chapter 5

Coupling and Crosstalk

Whether in electronic or nanophotonic integrated systems, the signal transmitted in one channel would be coupled to another channel nearby and some undesired effects would occur. This phenomenon is defined as crosstalk. The crosstalk will become stronger as the reduction of the separation between two devices, which limits the integration density of the whole system.

As we mentioned previously, plasmonic devices can confine optical signal in a sub-wavelength region. So the corresponding crosstalk between plasmonic waveguides can be expected to be much smaller than dielectric waveguides. In this chapter, we will compare the coupling and crosstalk for different kinds of dielectric and plasmonic waveguides; then the way of further reduction of the crosstalk in plasmonic waveguides is proposed.

5.1 Coupling for Dielectric Waveguides and Plasmonic Waveguides

We will study the coupling properties of the plasmonic slot waveguide, and compare with two popular dielectric waveguides: Si waveguide and Si slot waveguide. The structure of these three kinds of waveguides are shown in Fig. 5.1: the Si waveguide is indeed a rectangular Si nanowire where the energy is mainly existed inside the Si core; the Si slot waveguide is composed by paralleling two Si waveguides together with a gap in between, and the light in the gap has high intensity; by replacing the Si to metal for the Si slot waveguide, the plasmonic slot waveguide is obtained, followed by a subwavelength mode confinement. For the purpose of comparison, the hight of the waveguides are all set to be $h = 250\,\text{nm}$ which is the thickness on a standard SOI wafer.

Here, to clearly characterize the coupling properties, a parameter of coupling length [59] is proposed which is defined as
CHAPTER 5. COUPLING AND CROSSTALK

Figure 5.1: (a) Cross sections of two parallel Si waveguides (top), two parallel Si slot waveguides (middle) and two parallel plasmonic slot waveguides (bottom); (b) The dependence of the coupling length $L_C$ on the distance $d$ between the center of the waveguides.

\[ L_C = \frac{\pi}{|\beta_s - \beta_a|} \] (5.1)

which is the distance where the maximum energy can be transmitted from one waveguide to another; $\beta_s$ and $\beta_a$ are propagation constants for the symmetric and anti-symmetric modes. All the simulation results are obtained by the commercial software COMSOL Multiphysics.

Take the coupling length $L_C = 25\mu m$ as a standard, which corresponds to a $\sim 24dB/\mu m$ crosstalk, the corresponding separations $d$ are 260, 655 and 930nm for the plasmonic slot, Si and Si slot waveguides. It is obviously that the plasmonic slot waveguide is much superior in crosstalk compared with dielectric waveguides, which is caused by its excellent mode confinement. To realize a low crosstalk and high density integration system, plasmonic devices are good candidates.

5.2 Reducing Crosstalk between Nanowire-based Hybrid Plasmonic Waveguides

Compared with dielectric waveguides, plasmonic waveguides are demonstrated to have a much lower crosstalk. Structural modifications such as changing the orientation of the metal surfaces or adding a metallic slab in between can be made to further reduce the crosstalk.
5.2. REDUCING CROSSTALK BETWEEN NANOWIRE-BASED HYBRID PLASMONIC WAVEGUIDES

5.2.1 Nanowire based Hybrid Plasmonic Waveguide

As shown in the Fig. 5.2(a), the HP waveguide is composed by a dielectric nanowire on a metal surface. The dielectric nanowire has a relatively high index core with a diameter $d$, covered by a low index cladding with a thickness $t$. For our simulation purpose, we consider a silver substrate and choose silicon and silica as the materials for the core and cladding of the nanowire respectively. We focus on the optical communication wavelength of 1550$\text{nm}$, the corresponding material constants are $\varepsilon_{\text{Si}} = 11.9$, $\varepsilon_{\text{SiO}_2} = 2.1$, and $\varepsilon_{\text{Ag}} = -129 - 3.3i$ [60]. The silica coating layer can be formed by oxidizing the silicon nanowire in experiments [61–64]. The thickness of the oxide layer can be controlled by carefully setting the oxidation condition. The cladding thickness $t$ therefore determines the separation between the silicon nanowire and the silver substrate.

Figure 5.2: (a) Cross-section of two parallel HP waveguides with a separation of $s$; (b) Coupling length $L_C$ (red solid line) for the HP waveguides as a function of the separation $s$, compared with $L_C$ for the pure dielectric waveguides composed by two bare nanowires with $d = 300\text{nm}, t = 12\text{nm}$ (blue dashed line). The mean attenuation length $L_P$ is plotted in black dot-dashed line; (c) Maximum power transfer $P_{\text{max}}$ for the HP waveguides as a function of the separation $s$ between two HP waveguides.
To study the crosstalk between the HP waveguides, we firstly consider the simplest condition that two nanowires is placed in parallel together on top of a metal substrate. Owing to the existence of propagation loss, even for two identical HP waveguides, a 100% coupling efficiency cannot be achieved. If the power is input into one HP waveguide, the maximum power obtainable in the other HP waveguide due to coupling is

\[ p_{\text{max}} \simeq \exp(-2\chi \arctan(1/\chi)) \frac{1}{1 + \chi^2}, \quad \chi = \frac{2L_C}{\pi L_P} \] (5.2)

Given the complex propagation constants \( \beta_s + i\alpha_s \) and \( \beta_a + i\alpha_a \) for the symmetric and anti-symmetric modes, we have \( L_P = 2/(\alpha_s + \alpha_a) \) to be the mean attenuation length which is approximately twice of the propagation length for weak coupling. And the length to achieve the maximum power transfer \( p_{\text{max}} \) is defined as \( L_{\text{max}} \).

It is known that for the directional coupling, large coupling length \( L_C \) or small maximum power transfer \( p_{\text{max}} \) stands for low crosstalk. So what we will do is to design an optimal structure which can increase the coupling length \( L_C \) and decrease the maximum power transfer \( p_{\text{max}} \).

In our simulations of the crosstalk and coupling, the parameters of the nanowires are set to be \([d, t] = [300, 12]\) nm. The dependence of the coupling length \( L_C \) on the separation \( s \) between the centers of these two HP waveguides is shown in Fig. 5.2(b) (red-solid line). As a comparison, the coupling length \( L_C \) for the coupling between two identical nanowires without the metallic substrate is also shown in Fig. 5.2(b) (blue-dashed line). Obviously, with the same separation \( s \), the coupling length \( L_C \) for the HP waveguides is much larger than the dielectric waveguides. This means that the HP waveguides have much lower crosstalk than the dielectric waveguides. Take \( s = 1000 \) nm for example, the coupling length \( L_C \) for the HP waveguides is about 20 times larger than that of the dielectric waveguides. For a shorter separation, such as \( s = 450 \) nm, which is close to the cutoff of the anti-symmetry mode for a dielectric waveguides, the coupling length \( L_C \) for the HP waveguides is also about 2 times larger. The low crosstalk is due to the subwavelength mode confinement of the HP waveguides. Since most of the electromagnetic energy is highly confined in the gap, the mode overlap between the two HP waveguides is much weaker than that between the dielectric waveguides. The almost linear dependence of the coupling lengths on the waveguide separation is due to the fact that for a relatively weakly coupled waveguide pair the coupling length \( L_C \) increases with the separation \( s \) as \( \sim \sqrt{s} \exp(\alpha s) \), where \( \alpha = \frac{2\pi}{\lambda} \sqrt{n_{\text{eff}}^2 - n_{\text{clad}}^2} \) is the decay constant and \( n_{\text{clad}} = 1 \) (air) in our investigation. The constant slopes observed in Fig. 5.2(b) (in semi-log plot) are precisely determined by the decay constant \( \alpha \) (while the effect of the factor \( \sqrt{s} \) is much less significant). More specifically, our proposed HP waveguide has a \( n_{\text{eff}} = 2.05 \) and that without a metallic substrate has a \( n_{\text{eff}} = 1.25 \): their corresponding decay constants are 7.26 and 3.04, in accordance
5.2. REDUCING CROSSTALK BETWEEN NANOWIRE-BASED HYBRID PLASMONIC WAVEGUIDES

with Fig. 2d in that the slope for the HP waveguide system is much larger than that for the dielectric system.

The maximum power transfer $p_{max}$ is another parameter to examine when one assesses the effect of crosstalk between two waveguides. As shown in Fig. 5.2(c), for the above-mentioned two HP waveguides $p_{max}$ decreases rapidly as the separation $s$ increases. When $s = 960 \text{nm}$, one has $p_{max} = 0.1$, which means at most 10% power can be transferred from one HP waveguide to the other. It should however be reminded that care should be taken for interpreting $p_{max}$ since the parameter is also highly related to the propagation loss of the waveguide under consideration. A low value of $p_{max}$ most often suggests a high propagation loss in the waveguide system. A cross-comparison of $p_{max}$ is only meaningful if two systems are made of the same type of element waveguides. In the following discussions, we concentrate on crosstalk in systems based on the same HP waveguides illustrated in Fig. 5.2(a). Therefore the maximum power transfer $p_{max}$ can be considered as an effective parameter to compare the performances of these systems.

5.2.2 Further Decrease Crosstalk between Hybrid Plasmonic Waveguides

Although HP waveguides lead to much lower crosstalk than the corresponding dielectric waveguides, many improvements can be done to further decrease the crosstalk.

One approach is shown in Fig. 5.3(a), where the metal surfaces are placed vertically. The substrate of a single HP waveguide is rotated by 90 degrees compared to the structure in Fig. 5.3(a). As shown in Fig. 5.3(b), the electric field is well confined in the gap between the nanowires and the metallic slot in vertical direction. Compared with the structure shown in Fig. 5.2, when the separation $s$ between the centers of the two nanowires is the same, the distance between the gaps of the two HP waveguides increases by more than $300 \text{nm}$. So a reduction of crosstalk can be expected for the HP waveguides with vertical substrates. In contrast to the normal HP waveguides in Fig. 5.2, the coupling length $L_C$ for the HP waveguides with vertical substrates increases to be about 5 times larger (Fig. 5.3(c)) for any separation $s$. The almost identical slopes for the $L_C \sim s$ curves found for the two types of waveguide systems are due to the fact that they are composed by essentially the same element waveguides, as we have discussed in the previous section. For a HP waveguide with a vertical substrate, its effective index is $n_{eff} = 2.08$; therefore the decay constant is $\alpha = 7.39$, which is very close to that for a normal HP waveguide with horizontal substrate ($\alpha = 7.26$). We also deduced the maximum power transfer $p_{max}$ for the system with vertical substrates as shown in Fig. 5.3(d). Compared with the normal HP waveguide system (also shown in the same figure), now $p_{max} = 0.1$ occurs at the separation $s = 730 \text{nm}$ which is much smaller than the separation $s = 960 \text{nm}$ for the normal HP waveguide system. The
CHAPTER 5. COUPLING AND CROSSTALK

Figure 5.3: (a) Cross-section of two parallel HP waveguides with vertical substrates and a separation $s$ between two nanowires; (b) Distribution of $E_x$ field for the symmetric mode of the coupled HP waveguides system with $d = 300\, \text{nm}$, $t = 12\, \text{nm}$, $s = 500\, \text{nm}$; (c) Coupling length $L_C$ (red solid line) for the metal-slot HP waveguides as a function of the separation $s$ between two HP waveguides, compared with $L_C$ for the normal HP waveguides (blue dashed line). The mean attenuation length $L_P$ for the metal-slot HP waveguides is plotted in black dot-dashed line. (d) Maximum power transfer $p_{max}$ for the metallic slotted HP waveguides as a function of the separation $s$ between two HP waveguides.

result indicates that the HP waveguides with vertical substrates can give rise to the same crosstalk as the normal HP waveguides within a much smaller volume.

Another straightforward way to reduce the crosstalk between two HP waveguides is to use a metallic block in between of the waveguides (Fig. 5.4(a)). It is obviously that both the width $w$ and the height $h$ of the slab will influence the coupling efficiency. Here, as the separation is set to a fixed value $s = 500\, \text{nm}$, the distance between the neighboring edges of the two HP waveguides is only $176\, \text{nm}$. Controlling the polarization to TM, there is only a fundamental TM mode existing for such HP waveguides (Fig. 5.4(b)). The variation of the corresponding coupling length $L_C$ and the maximum power transfer $p_{max}$ for different width $w$ and height $h$ is studied. The results are shown in Fig. 5.4(c) and (d). With an increase in either
5.2. REDUCING CROSSTALK BETWEEN NANOWIRE-BASED HYBRID PLASMONIC WAVEGUIDES

Figure 5.4: (a) Cross-section of two parallel HP waveguides composed by placing a metallic block (with a width $w$ and height $h$) between the nanowires with a separation $s$; (b) Distribution of $E_y$ field for the symmetric mode of such HP waveguides with $d = 300\,\text{nm}$, $t = 12\,\text{nm}$, $s = 500\,\text{nm}$; (c) Coupling length $L_C$ for such HP waveguides with the separation $s = 500\,\text{nm}$ and different width $w$ as a function of the height $h$ between the two HP waveguides. The mean attenuation length $L_P$ is also plotted in dot-dashed line with the same color as $L_C$; (d) Maximum power transfer $p_{\text{max}}$ for such HP waveguides with the separation $s = 500\,\text{nm}$ and different width $w$ as a function of the height $h$ between the two HP waveguides.

The height $h$ or the width $w$, the coupling length $L_C$ increases and the maximum power transfer $p_{\text{max}}$ decreases. For a slab with a width $w = 150\,\text{nm}$ and a height $h = 600\,\text{nm}$, the coupling length is $L_C = 3.3 \times 10^3\,\mu\text{m}$ which is $\sim 500$ times larger than that without the metallic slab ($L_C = 6.5\,\mu\text{m}$). With the decrease of the width $w$, the coupling length $L_C$ also decreases. However, even when the slab has a width $w = 50\,\text{nm}$ and a height $h = 600\,\text{nm}$, the coupling length is $L_C = 86\,\mu\text{m}$ which is still more than 10 times larger than that without the metallic slab. More information can be obtained from the variation of the maximum power transfer $p_{\text{max}}$ shown in Fig. 5.4(d). For a slab with a height $h = 600\,\text{nm}$ and a width $w = 100\,\text{nm}$ the maximum power transfer is $p_{\text{max}} = 0.01$, by which the crosstalk is much lower compared with that without the metallic slab ($p_{\text{max}} = 0.9$). With the increase of
the width $w$, the maximum power transfer $p_{\text{max}}$ keeps decreasing to an even smaller value, at $< 3 \times 10^{-4}$ when $w = 150\,\text{nm}$. 
Chapter 6

Plasmonic Cavities

There has been a great amount of interests in the research of optical cavities in the last few decades. Such optical cavities are vital for a wide range of applications [65] such as cavity quantum electrodynamics, on-chip light sources (lasers, LEDs, etc), controlled spontaneous emission, optical filters, etc. Different kinds of optical cavities have been proposed, such as photonic crystal cavities [66], dielectric nanowire cavities [67], dielectric ring or disk cavities [68], metal-dielectric cavities [69], etc. In some special applications as single photon sources [70], high-speed modulated lasers [71], threshold-less lasing [72], and investigations of light-matter interactions [73], a cavity with a high quality factor $Q$ and a small volume $V$, hence a high ratio between the two (recognized as Purcell factor $F_P$ [74]), is desired.

For these optical cavities, although extremely high $Q$ factors can be achieved, the mode volumes $V$ are limited by the diffraction limit. Therefore achieving a high $F_P$ with these designs is still out of reach. Recently, more and more attention has been paid to plasmonic cavities [73,75–78]. Plasmonic devices are based on the effect of surface plasmon polariton, which is capable of confining an electromagnetic field at a deep-subwavelength scale. Correspondingly a plasmonic cavity can efficiently reduce the mode volume to an ultra small value. However, the existence of Ohmic loss in metals inevitably impinges on the achievable $Q$ factors. The remaining challenge is therefore to reduce the adverse effect of the Ohmic loss inherent to metals deployed in plasmonic light-confining systems.

In this thesis, we will theoretically study nanodisk cavities based on hybrid plasmonic structures. With an enhancement of the electromagnetic field inside the low-index layer between a metallic layer and a high-index layer, HP structures can realize a good confinement and relatively low propagation loss simultaneously. So it is possible to realize high $Q$ factors and small volumes simultaneously.
6.1 HP Nanodisk

The proposed HP nanodisk is depicted in Fig. 6.1. Such a HP nanodisk can be fabricated by a two-step process: Firstly fabricating a standard SOI nanodisk which is composed by a 250nm-thick silicon nanodisk on the 3µm-thick silica substrate. It can be realized by the electron beam lithography (EBL) and the inductively coupled plasmon (ICP) etching; then a low-index layer and a silver layer are defined on the top of silicon nanodisk by a second time EBL patterning followed by a lift-off process. Here, the low-index layer are proposed to work as the gain medium for laser and can be fabricated by doping quantum dots nanocrystals inside the silica layer [79].

Figure 6.1: Schematic diagram of the HP nanodisk. The inset shows the cross section of the HP nanodisks: silicon layer has a height \( h_{Si} \); a low-index layer has a height \( h_L \); and silver layer has a height \( h_{Ag} \).

A 3D-FDTD method is used here to obtain the field patterns, \( Q \) factors, mode volumes and the resonant wavelengths of the HP nanodisks. Because the operating wavelength is around the telecommunication wavelength \( \lambda = 1550nm \), the permittivities of the SOI are set to be \( \varepsilon_{Si} = 11.9, \varepsilon_{SiO_2} = 2.1 \); the permittivity of the low-index layer should be higher than silica as the existence of the doping, so we set it to be \( \varepsilon_L = 3 \) for convenient; and the dispersive permittivity of the silver is calculated according to a Drude model fitted with the experiment data [60]. In the simulations, the heights of the low-index layer and the silver layer are firstly set to be \( h_L = 50nm \) and \( h_{Ag} = 100nm \), by which a balance between the propagation loss and the mode confinement can be realized.
For the proposed HP nanodisks, there are two different types of modes existing: TE mode which is a dielectric-like mode with most electromagnetic energy concentrated in the silicon layer; and TM mode which is a plasmonic-like mode with most electromagnetic energy confined in the low-index layer. In order to achieve a subwavelength mode confinement and therefore to reduce the mode volume, we only discuss the TM modes. For nanodisk cavities, there are usually three mode numbers applied to classify the resonant modes, corresponding to the vertical, radial and azimuthal directions. Here only the fundamental modes in vertical and radial directions are investigated since these modes have relatively higher $Q$ factors and smaller mode volumes compared to the other supported modes. In this case, the modes of the proposed HP nanodisks can be classified with only the azimuthal mode numbers $m$.

![Figure 6.2: (a)The $E_z$ field distribution in the center of the low-index layer for a HP nanodisk with the radius $r = 670\,nm$ at $\lambda = 1552\,nm (m = 5)$. The violet line shows the edge of the low-index layer; (b)The $E_z$ field distribution in the $x-z$ plane (half). The white and red solid line shows the silver and silicon layer, blue-dashed line shows the surface of the silica layer.](image)

In our FDTD simulations, we firstly use a broad-band Gaussian pulse to excite all of the TM resonant modes in the chosen bandwidth and then re-run the simulation with narrow-band sources around these modes to obtain the field patterns. For a HP nanodisk with a radius $r = 670\,nm$, a resonant mode exists at the wavelength $\lambda = 1552\,nm$ with the azimuthal number $m = 5$. The profile of the electric field $E_z$ in the center plane of the low-index layer is shown in Fig. 6.2(a). To further elucidate the mode confinement, the profile of the electric field $E_z$ in the vertical direction is also shown in Fig. 6.2(b). The electric field is strongly concentrated within the low-index layer and near the sidewall that a relatively small mode volume can be expected.
6.2 Simulation Results

For a nanodisk cavity, $Q$ factor is one of the most vital parameters to evaluate the optical properties. To achieve a high $Q$ factor, a common practice is to increase the radius which can effectively decrease the bending loss. However, for a HP nanodisk, a large radius also means a large propagation loss which will in turn reduce the $Q$ factor. Meanwhile, the increase of the radius will increase the mode volume and influence the Purcell factor.

Table 6.1: Performance of HP nanodisks with different radii

<table>
<thead>
<tr>
<th>Radius (nm)</th>
<th>m</th>
<th>Wavelength (nm)</th>
<th>$Q$</th>
<th>$V_{eff}((\lambda_0/2n)^3)$</th>
<th>$F_P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>320</td>
<td>2</td>
<td>1569</td>
<td>21</td>
<td>0.036</td>
<td>359</td>
</tr>
<tr>
<td>440</td>
<td>3</td>
<td>1555</td>
<td>59</td>
<td>0.062</td>
<td>579</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1273</td>
<td>169</td>
<td>0.145</td>
<td>708</td>
</tr>
<tr>
<td>560</td>
<td>3</td>
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6.2. SIMULATION RESULTS

We have done FDTD simulations on a number of HP nanodisks whose radii are respectively 320, 440, 560, 670, 780, 890 and 1000 nm. These nanodisk cavities have a resonant mode near the $\lambda = 1550$ nm, achieved at various azimuthal mode number $m = 2 \sim 8$. Our FDTD simulation results are summarized in Table 6.1 for a detailed comparison of the nanodisk performances. Notice that resonances falling into the telecommunication wavelength regime are highlighted in bold. The effective mode volume is calculated as

$$V_{\text{eff}} = \frac{\int \varepsilon(x, y, z) |E(x, y, z)|^2 dz dy dz}{\max \{ \varepsilon(x, y, z) |E(x, y, z)|^2 \}}$$  \hspace{1cm} (6.1)

and the Purcell factor is calculated as

$$F_P = \frac{3}{4\pi^2} \left( \frac{\lambda_0}{n} \right)^3 \left( \frac{Q}{V_{\text{eff}}} \right)$$  \hspace{1cm} (6.2)

where $\lambda_0$ is the resonant wavelength in vacuum and $n$ is the refractive index of the gain medium with $n = \sqrt{3}$. From Eq. 6.2, it is known that in order to obtain a high Purcell factor, it is better to use the resonant mode with a high $Q$ factor and small mode volume.

All the modes supported by these HP nanodisks in the wavelength range of 1200 $\sim$ 2000 nm are listed in Table 6.1. As the increase of the radius, more modes can be supported in a HP nanodisk. For a HP nanodisk with $r = 1000$ nm, 6 modes are supported in the interested wavelength range, whereas there is only 1 mode for a nanodisk with $r = 320$ nm. For a HP nanodisk with a certain radius, as the increase of the azimuthal number $m$, the corresponding $Q$ factor will also increase. It is caused by the fact that a larger azimuthal number $m$ means a smaller resonant wavelength, where both the radiation loss and the propagation loss are smaller. Meanwhile, as the azimuthal number increases, the mode volume also increases. The variation of the Purcell factor $F_P$ is no longer monotonic, since the Purcell factor depends on both the $Q$ factor and the mode volume. Shown in the last column of Table 6.1, for the HP nanodisk with a small radius ($r < 890$ nm), the Purcell factor $F_P$ always increases as the azimuthal number $m$ increases; but for the HP nanodisk with a large radius ($r \geq 890$ nm), as the increase of the azimuthal number $m$, the Purcell factor $F_P$ increases firstly and then decreases.

For telecommunication applications, we are more interested in the resonant modes near 1550 nm, which has served as a guideline for us to choose the radii of these HP nanodisks in the design. As a comparison, we plot the $Q$ factors, mode volumes $V_{\text{eff}}$ and Purcell factors $F_P$ of these modes in Fig. 6.3. As the azimuthal number $m$ increases from 2 ($r = 320$ nm) to 8 ($r = 1000$ nm), the $Q$ factor increases from 21 to 819 (See Fig. 6.3(a), red line), which is accompanied by the increase of the mode volume from 0.036 to 0.273($\lambda_0/2n)^3$ (See Fig. 6.3(a), blue line). To
obtain a high $Q$ factor, a HP nanodisk with a large radius (such as $r = 1000nm$) is a good choice. The dependence of the Purcell factor $F_P$ on the azimuthal number $m$ is plotted in Fig. 6.3(b). As $m$ increases from $2 (r = 320nm)$ to $7 (r = 890nm)$, $F_P$ increases from 359 to 1824 and changes a little to 1827 as $m$ further increases to $8 (r = 1000nm)$. It means a HP nanodisk with a radius of $r = 890nm$ is large enough to realize a high Purcell factor.

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Above we have investigated the HP nanodisks with $h_L = 50nm$. Since the electro-
6.2. SIMULATION RESULTS

magnetic field is strongly concentrated inside the low-index layer, the parameters such as $Q$ factor, mode volume $V_{\text{eff}}$ are sensitive to the variation of the height $h_L$. Here we assess such influence by calculating the modes for HP nanodisks with a fixed radius of 670nm at various height values for the low-index layer. Table 2 presents the simulation results when the low-index layer height changes from $h_L = 40$ to 60nm.

When the height varies from $h_L = 40$ to 60nm, there are always 4 modes supported in the examined wavelength range of 1200 $\sim$ 2000nm. Looking at the modes with the same azimuthal mode number $m$, as $h_L$ increases, the mode volume increases apparently due to the larger geometry volume of the low-index layer. The variation of $Q$ factor is more complex: for the modes with $m = 4, 5$, the $Q$ factor decreases as $h_L$ increases; for the mode with $m = 7$, the opposite trend is noticed; whereas for the mode with $m = 6$, the nanodisk with $h_L = 50$nm has the highest $Q$ factor. This interesting phenomenon is caused by the trade-off between the radiation loss and the propagation loss: as the height of the low-index layer increases, the propagation loss of the HP nanodisk decreases combined with the increase of the radiation loss cause by the worse mode confinement. The variation of the Purcell factor is simple that $F_P$ monotonically decreases as $h_L$ increases for any $m$. 

Chapter 7

Conclusion and Future Work

In this thesis, we mainly focus on the optical properties of plasmonic waveguides and resonators with their applications in optical telecommunications. Superior to conventional optical devices with diffraction limit, plasmonic devices can easily confine light in a deep subwavelength scale that makes them excellent candidates for the next-generation high density electronic-photonic integrations.

In Chapter 2, the basic theories and optical properties of the surface plasmon polaritons are introduced. Derived from Maxwell’s equations, it is known that only TM modes can be supported by SPPs and there is always a trade-off between the mode confinement and the propagation length. From the motion equation of the free electron gas, a Drude model is deduced which is used to describe the dispersive permittivities of metals.

In Chapter 3, we briefly summarize two numerical methods which are widely used in this thesis: the Finite Element Method which is used to obtain the eigen-modes of the waveguides; and the Finite-Difference Time-Domain Method which is used to study the propagation properties of the electromagnetic waves in time domain.

In Chapter 4, a HP linear taper coupler is proposed to efficiently couple the optical signal from a standard SOI waveguide to a HP waveguide. Compared with a direct coupling or a SOI linear taper, a significant improvement can be obtained in a broadband wavelength range. The experimental result is also investigated which agrees well with the numerical simulation. To connect one SOI waveguide with several HP waveguides, HP MMI power splitters are proposed. With optimized parameters, the balanced splitting with high transmissions can be realized for a $1 \times 3$ and a $1 \times 2$ HP MMI power splitters.

In Chapter 5, we theoretically study the coupling and crosstalk for different waveguides. Compared with dielectric waveguides, plasmonic waveguides require
much shorter separation in between for the same coupling length which stands for much lower crosstalk. By placing a metallic block in between, a further reduction of the crosstalk is obtained for the designed HP waveguides.

In Chapter 6, HP nanodisk cavities are proposed. For a HP nanodisk with optimized parameters, a high $Q$ factor and a high Purcell factor can be realized simultaneously. The thickness of the gain medium layer is also studied for a purpose of further optimization.

For the future work, there are many topics we are interested in.

(1) For the HP MMI power splitters, we can do some experimental demonstrations and even combine them with other devices like Mach-Zehnder interferometers, cavities, etc.

(2) A metallic block is used to reduce the crosstalk between the HP waveguides. With modifications of the shape and size of the block, further improvements can be expected.

(3) For the HP nanodisk cavities, we can also do experiments to characterize the properties. By combining HP plasmonic cavities with other kinds of plasmonic devices, or even with dielectric devices, some special phenomena and functions can be expected such as Fano resonances, optical filters, biosensors, etc.
Chapter 8

Guide to the Papers

**Paper I:** Yi Song, Jing Wang, Min Yan, and Min Qiu, "Efficient coupling between dielectric and hybrid plasmonic waveguides by multimode interference power splitter", J. Opt., 13, 075002, 2011.

*Author’s contribution:* I did the simulation and analyzed the influence of geometry and wavelength to the splitter. I finished the first draft of the manuscript.

**Paper II:** Yi Song, Jing Wang, Min Yan, and Min Qiu, "Subwavelength hybrid plasmonic nanodisk with high Q factor and Purcell factor", J. Opt., 13, 075001, 2011.

*Author’s contribution:* I did the simulation and analyzed the resonance modes. I finished the first draft of the manuscript.


*Author’s contribution:* I did the simulation and analyzed the crosstalk properties. I finished the first draft of the manuscript.


*Author’s contribution:* I did the simulation of the coupling properties between
the waveguides.

**Paper V:** Yi Song, Jing Wang, Qiang Li, Min Yan, and Min Qiu, "Broadband coupler between silicon waveguide and hybrid plasmonic waveguide", Opt. Express., volume 18(12):13173-13179, 2010.

*Author’s contribution:* I did the simulation and analyzed the method to improve the coupling efficiency. I finished the first draft of the manuscript.


*Author’s contribution:* I participated in the design of the coupler.

**Paper VII:** Bozena Jaskorzynska, Yi Song, and Min Qiu, "Tradeoff between mode confinement, loss, and cross-talk, for dielectric and metal slot waveguides", Photonics Letters of Poland, 1(4), 172-174, 2009.

*Author’s contribution:* I did the simulation of the directional coupling and analyzed the coupling efficiency.
Bibliography


