文章编号 1674-2915(2010)01-0089-04

Basic properties of trapezoidal channel plasmon polariton subwavelength waveguides

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Abstract: An air channel inside a silver metal film is usually used as a typical Channel Plasmon Polariton (CPP) waveguide. This paper presents research on the basic properties of this waveguide using the Finite Difference Time Domain (FDTD) method. The relationship between transmission power and structure of the waveguide is investigated. The simulation results show that the subwavelength trapezoidal CPP waveguide is superior to the rectangle CPP waveguide for controlling SPP radiation loss and enhancing the transmitted power. As a result, if the rectangle CPP waveguide is replaced by a trapezoidal CPP waveguide in certain integrated optical devices, their performance may be improved.

Key words: CPP; subwavelength; trapezoidal waveguide; FDTD

1 Introduction

The size of optical elements is close to the practical limit because of the diffraction effect of light. As one of the promising ways to guide optical waves beyond the diffraction limit, low-dimensional optical waveguides have been receiving much attention in recent years[1]. According to the definition of the dimension of optical waves[2], a Surface Plasmon Polariton (SPP) propagating along a planar metal-dielectric interface is classified as a two-dimensional (2D) optical wave. A typical 2D optical waveguide structure is a dielectric thin film sandwiched between the two semi-infinite metals. When the metal or dielectric film is thin enough, the SPPs generated on each metal-dielectric interface will couple, and turn into channel plasmon polaritons.

As a departure from the rectangle CPP waveguides reported in recent years[3-6], a trapezoidal-shaped CPP waveguide is proposed as an elementary unit for use in integrated optical devices. The transmission characteristics of this waveguide are studied and compared with those for rectangle CPP waveguides using Finite Difference Time Domain (FDTD) simulations.

2 Channel Plasmon Polaritons (CPPs)

The structure of typical 2D optical waveguide is shown in Fig. 1. It is necessary to give a brief description of CPPs travelling in the sub-wavelength

Received date: 2009-11-21; Revised date: 2009-12-23.

Foundation items: supported by the Major State Basic Research and Development Program of China (973 Program) (2006CB302900); National Nature Science Foundation of China (60772026).

channel sandwiched between the two planar metal surfaces extended infinitely in the y-axis direction. In this paper, only the TM mode consisting of E_x, E_z, and H_y components is discussed.

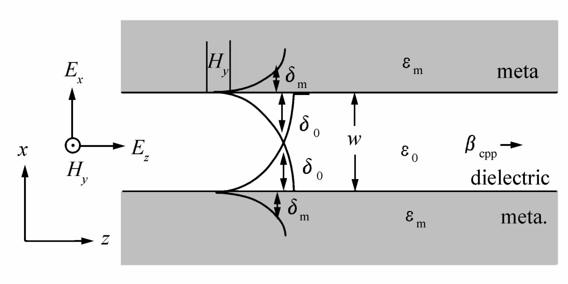

Fig. 1 Structure of the CPP waveguide, $\delta_0 = [\mathrm{Re}(k)]^{-1}$ and $\delta_m = [\mathrm{Re}(p)]^{-1}$ represents the penetration depth of SPP in the dielectric and metal, respectively.

Assuming the incident plane is the x-z plane, the TM wave H_y field component can be expressed as $H_y = yH_0 e^{i(k_0 z - wt)}$, where $k_0 = 2\pi/\lambda$ is wave number in vacuum. Omitting the time factor, the SPPs excited in the metal and dielectric can be expressed as

$$H_y = \begin{cases} A_0 e^{-p(x-\frac{w}{2})} e^{i\beta_{spp}z}, (x > \frac{w}{2}) \\ B_0 e^{kx} e^{i\beta_{spp}z} + C_0 e^{-kx} e^{i\beta_{spp}z}, (-\frac{w}{2} < x < \frac{w}{2}) \\ D_0 e^{p(x+\frac{w}{2})} e^{i\beta_{spp}z}, (x < -\frac{w}{2}) \end{cases} \tag{1}$$

where k and p are the wave numbers in the dielectric and metal, respectively, decide the penetration depth of SPPs (as shown in Fig. 1, $\delta_0 = [\mathrm{Re}(k)]^{-1}$ and $\delta_m = [\mathrm{Re}(p)]^{-1}$, β_{spp} is the propagation constant of the coupled CPPs, A_0, B_0, C_0 and D_0 are the amplitudes of SPP transmission mode in dielectric and metal, and w is the width of the dielectric channel between the two semi-infinite metals.

According to the Maxwell equations and the continuity of H_y and E_z, Eq. (1) can be derived:

$$\begin{cases} A_0 = B_0 + C_0 e^{-kw} \\ B_0 e^{-kw} + C_0 = D_0 \\ \frac{-pA_0}{\varepsilon_m} = \frac{kB_0}{\varepsilon_0} - \frac{k}{\varepsilon_0} C_0 e^{-kw} \\ \frac{k}{\varepsilon_0} B_0 e^{-kw} - \frac{k}{\varepsilon_0} C_0 = \frac{p}{\varepsilon_m} D_0 \end{cases} . \tag{2}$$

By solving Eq. (2), the CPP dispersion equation can be expressed as follow:

$$\frac{\varepsilon_0 p}{\varepsilon_m k} = \frac{1 + \exp(kw)}{1 + \exp(kw)}, \tag{3}$$

where

$$\begin{cases} k = k_0 \sqrt{(\frac{\beta_{CPP}}{k_0})^2 - \varepsilon_0} \\ p = k_0 \sqrt{(\frac{\beta_{CPP}}{k_0})^2 - \varepsilon_m} \end{cases}, \tag{4}$$

here ε_0 and ε_m are the dielectric constants of the medium in the dielectric and metal, respectively. ε_m can be calculated from the Drude formalism $\varepsilon_m(\omega) = 1 - \omega_p^2/[\omega^2 + i\gamma\omega]$, where ω_p is the plasma frequency, γ is the absorption and ω ($\omega = ck_0$, c is the velocity of light in vacuum) is the frequency of the source, respectively. CPPs effective index can be given by

$$n_{eff} = \frac{\beta_{CPP}}{k_0} \tag{5}$$

When the channel width is very small, some guiding modes can propagate in the air gap. In order to establish a quantitative understanding, Fig. 2

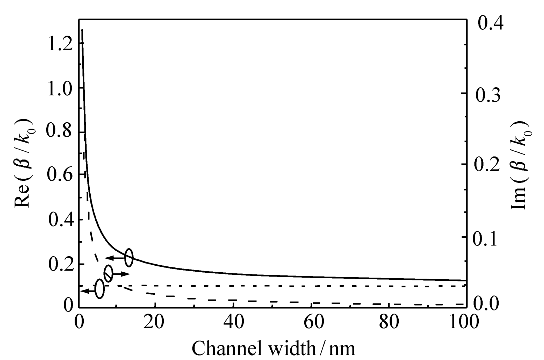

Fig. 2 Dependence of complex propagation constant of CPPs in guide region (channel) on the channel width at wavelength of 650 nm.

presents the propagation constant Re[β] (solid curve) and the loss Im[β] (dashed curve) of the CPPs in guiding region for different widths w, where $\varepsilon_0 = 1$ for air and ε_m for silver at 650 nm. The dotted curve corresponds to the propagation constant for the electromagnetic wave in vacuum. In narrow channels, both the real and imaginary parts of the CPPs propagation constant increase rapidly, implying the reduced propagation speed of CPPs as well as increased loss per unit length.

3 Simulation and results

According to earlier researches, when the source of excitation is a 650 nm TM-polarized plane wave, the optimal length of the CPPs waveguide leading to maximum transmitted power is 150 nm[4]. The same condition is chosen in our simulation. To determine how the structure will affect the transmitted power, the width of one end is fixed at 30 nm and the width of the other is varied. The simulation result is shown in Fig. 3, showing that the 30 nm/40 nm and 40 nm/30 nm (width of the input/output port) trapezoidal waveguide has more transmitted power than the rectangular one.

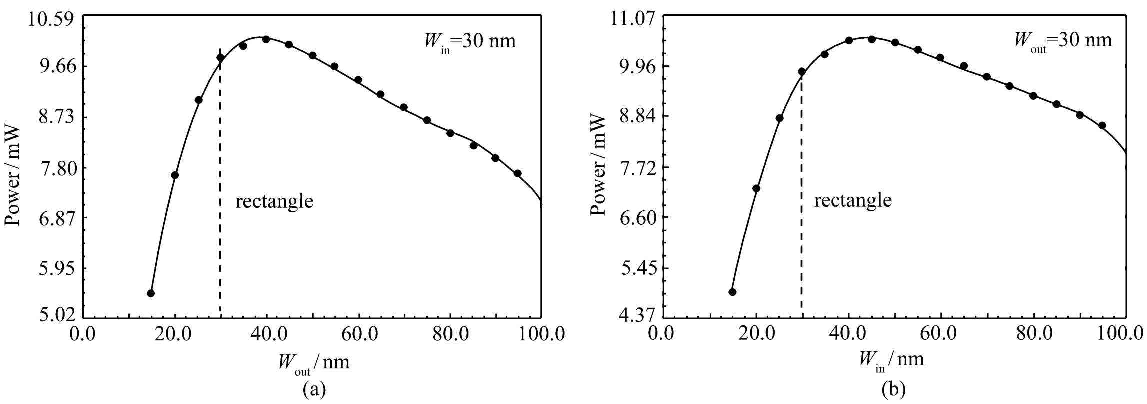

Fig. 3 (a) For $w_{in} = 30$ nm, the relationship between w_{out} and the transmitted power, (b) For $w_{out} = 30$ nm, the relationship between w_{in} and the transmitted power (w_{in} and w_{out} indicate the widths of the input port and output port).

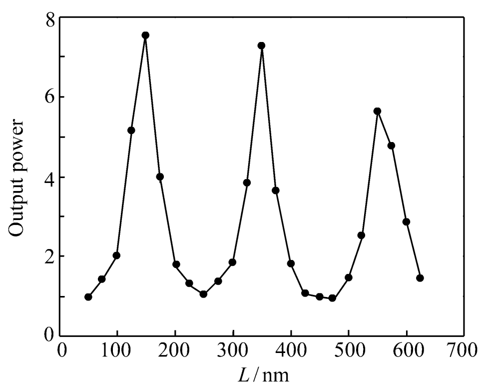

Fig. 4 Relationship between the length of trapezoidal-shaped waveguide and the transmitted power when the wavelength of the light source is 650 nm.

To determine whether the channel shape will affect the optimal length, the simulation result in Fig. 4 shows that the optimal length remains at 150 nm.

Based on the simulation result above, the trapezoidal-shaped CPPs waveguide is used as a basic element to constructe Y-shaped and multi-Y-shaped coupler. The Poynting vector $\boldsymbol{S}_z$ compared to the rectangle channel waveguide ($w = 30$ nm) is shown in Fig. 5. The transmitted power of the Y-shape and multi-Y-shaped couplers are higher than the traditional ones under the same input conditions.

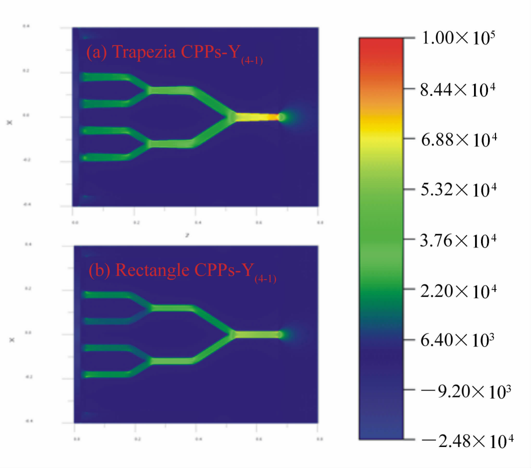

Fig. 5 Comparison of Poynting vectors of the *Y*-shaped, multi-*Y*-shaped couplers composed of trapezoidal and rectangular waveguides.

4 Conclusions

With the progress of nano integration technology, the development of CPP waveguides in integrated optics becomes more and more important. This paper presents a basic research on trapezoidal CPP waveguides and provides some reliable basis for more complex structures of CPP waveguides in future. Various types of waveguides consisting of trapezoidal CPPs and their construction scheme, which make the waveguide higher coupling efficiency and transmission efficiency, need more researches in the future.

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