Deep-subwavelength plasmonic mode converter with large size reduction for Si-wire waveguide: supplementary material

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1. Estimation of propagation loss

In waveguides that are uniform in the propagating direction (z direction), we can describe a propagating electric field as

$$\mathbf{E}(x, y, z) = \mathbf{E}_0(x, y) \exp[i(k_0 n_{\text{eff}} z - \omega t)], \quad (\text{S1})$$

where k_0 is the wavenumber in a vacuum and n_{eff} is the effective index. When n_{eff} is defined as $n_{\text{eff}} = n_r + in_i$, the field intensity is written as

$$|E(x, y, z)|^2 = |E_0(x, y)|^2 \exp(-2k_0 n_i z). \quad (\text{S2})$$

We estimated n_{eff} in the metal-insulator-metal (MIM) waveguide with the finite element method (FEM), and then we obtained the propagation loss from Eq. (S2). We show the propagation losses for various slot widths w_{slot} and Au thicknesses t_{Au} in Fig. S1. The calculated propagation losses for the 50×20 , 60×20 , and 70×20 -nm² slots ($w_{\text{slot}} \times t_{\text{Au}}$) were 1.3, 1.2, 1.2 dB/ μm , respectively. Those for the 50×30 and 50×40 -nm² slots were 0.98 and 0.84 dB/ μm , respectively.

Fig. S1. Propagation losses for various slot widths and Au thicknesses.

2. Numerical simulation of field enhancement factor

In this study, we evaluated the field intensity enhancement in MIM waveguides from the field enhancement factor η defined as

$$\eta = \left(\int_{\text{slot}} |E|^2 dS / \int_{\text{slot}} dS \right) / \left(\int_{\text{Si-wire}} |E|^2 dS / \int_{\text{Si-wire}} dS \right), \quad (\text{S3})$$

which is the ratio of the electric field intensity averaged over the cross-section of a MIM waveguide slot to that of a Si-wire waveguide core. Here, we estimated η at the entrance of a MIM waveguide for a taper length l_{taper} of 600 nm with an FEM

calculation. When we define the field intensity at the entrance of the MIM waveguide as $|E_1|^2$, η at the entrance is given by

$$\eta = \left(\int_{\text{slot}} |E_1|^2 dS / \int_{\text{slot}} dS \right) / \left(\int_{\text{Si-wire}} |E|^2 dS / \int_{\text{Si-wire}} dS \right). \quad (\text{S4})$$

However, Fabry-Perot oscillations are observed in the propagating field as shown in Fig. 2(a). Thus, we employed the following procedure to evaluate the field enhancement without the Fabry-Perot oscillations. From Eq. (S2), the field intensity in the MIM waveguide is described as

$$|E(x, y, z)|^2 = |E_1(x, y)|^2 \exp(-2k_0 n_i z). \quad (\text{S5})$$

The volume integration of Eq. (S5) is reduced to

$$\begin{aligned} \int_{\text{slot}} |E(x, y, z)|^2 dV \\ = \left(\int_{\text{slot}} |E_1(x, y)|^2 dS \right) \left(\int_{\text{slot}} \exp(-2k_0 n_i z) dz \right). \end{aligned} \quad (\text{S6})$$

As a result, we obtained the following expression,

$$\int_{\text{slot}} |E_1(x, y)|^2 dS = -2k_0 n_i \frac{\int_{\text{slot}} |E(x, y, z)|^2 dV}{\exp(-2k_0 n_i l_{\text{slot}}) - 1}, \quad (\text{S7})$$

where $\int_{\text{slot}} |E(x, y, z)|^2 dV$ and n_i are obtained with an FEM calculation. Then, we estimated the integrated field intensity at the entrance of the MIM waveguide. By contrast, the field intensity averaged over the cross-section of the Si-wire waveguide core was estimated by simulating the field propagation in the reference Si-wire waveguide. As a result, we obtained η at the entrance of the MIM waveguide as shown in Fig. 7.

3. Contribution of absorption, reflection, and scattering to total loss

The total loss of the entire structure includes the absorption, reflection, and scattering losses. We investigated the way in which these losses contribute to the total loss with an FEM calculation. Figure 2S(b) shows the l_{taper} dependence of the transmission, reflection, absorption, and scattering for an input power of 1 W in the entire structure (from the input waveguide to the output waveguide) [Fig. S2(a)]. Here, we estimated these values for $w_{\text{slot}} = 50$ nm, $t_{\text{Au}} = 20$ nm, and a gap $w_{\text{gap}} = 40$ nm between the Si taper and metal. The distance between the input and output Si-wire waveguide tips is fixed ($1 \mu\text{m}$), and the slot length l_{slot} is dependent on l_{taper} and w_{gap} . We first calculated the transmission, reflection, and absorption with the FEM, and then we obtained the scattering from the following relation,

$$\begin{aligned} &(\text{Transmission}) + (\text{Reflection}) \\ &+ (\text{Absorption}) + (\text{Scattering}) = 1. \end{aligned} \quad (\text{S8})$$

The absorption increases when l_{taper} increases. The reflection and scattering, on the other hand, are small when l_{taper} is long. As a result, the transmission is high for a long l_{taper} .

Figure 2S(c) shows the w_{gap} dependence of the transmission, reflection, absorption, and scattering for $l_{\text{taper}} = 600$ nm, $w_{\text{slot}} = 50$ nm, and $t_{\text{Au}} = 20$ nm. As w_{gap} is increased, the absorption decreases. We estimated the absorption only in the first converter to investigate the absorption in more detail. The absorption in the first converter is very high at $w_{\text{gap}} = 0$ nm. This indicates that most of the optical field is absorbed in the mode conversion. On the other hand, the reflection and scattering have their smallest values

around $w_{\text{gap}} = 20$ nm. They are large when $w_{\text{gap}} = 0$ nm or $w_{\text{gap}} = 100$ nm, but the scattering is more dominant at $w_{\text{gap}} = 100$ nm.

Fig. S2. (a) Schematic of the calculated structure. (b) Taper length dependence of the transmission, reflection, absorption, and scattering. (c) Gap width dependence of the transmission, reflection, absorption, and scattering.

4. Mode profiles for 40- and 100-nm gaps between Si taper and metal

The gap between the Si taper and metal plays an important role in mode conversion. Figure S3(a) is a top view of the calculated field profile ($|E_x|^2$) of a structure with $w_{\text{gap}} = 40$ nm. We input the optical field from the left Si-wire waveguide in the TE mode. The wavelength was 1550 nm. Figures S3(b) and S3(c) are cross-sectional mode profiles at $z = -1100$ and -800 nm, respectively. We also show the mode profiles for a structure with $w_{\text{gap}} = 100$ nm in Figs. S3(d)-S3(f). For $w_{\text{gap}} = 40$ nm, the side lobes are attracted to the gap in the tapered region [Figs. S3(b) and S3(c)], and the propagating mode is efficiently converted. For $w_{\text{gap}} = 100$ nm, however, the side lobes are widely distributed on the Si-wire waveguide side [Figs. S3(e) and S3(f)]. Here, the optical field that is not connected to the MIM waveguide is mainly scattered as shown in Fig. S2(c).

Fig. S3. (a)-(c) Calculated field profiles ($|E_x|^2$) of a structure with a slot length $l_{\text{slot}} = 0.90 \mu\text{m}$, a taper length $l_{\text{taper}} = 600 \text{ nm}$, a slot width $w_{\text{slot}} = 50 \text{ nm}$, an Au thickness $t_{\text{Au}} = 20 \text{ nm}$, and a gap width $w_{\text{gap}} = 40 \text{ nm}$. Cross-sectional top view at $y = 10 \text{ nm}$ (a). Cross-sectional side views at $z = -1100 \text{ nm}$ (b) and -800 nm (c). (d)-(f) $|E_x|^2$ of a structure with $l_{\text{slot}} = 0.52 \mu\text{m}$, $l_{\text{taper}} = 600 \text{ nm}$, $w_{\text{slot}} = 50 \text{ nm}$, $t_{\text{Au}} = 20 \text{ nm}$, and $w_{\text{gap}} = 100 \text{ nm}$. Cross-sectional top view at $y = 10 \text{ nm}$ (d). Cross-sectional side views at $z = -1100 \text{ nm}$ (e) and -800 nm (f). Scale bar, 500 nm in (a) and (d); 200 nm in (b), (c), (e), and (f).

5. Coupling losses for various Si-wire heights

We investigated how the Si-wire height h_{Si} affects the coupling loss. Figure S4 shows the h_{Si} dependence of the coupling loss for $l_{\text{taper}} = 600 \text{ nm}$, $w_{\text{slot}} = 50 \text{ nm}$, $t_{\text{Au}} = 20 \text{ nm}$, and $w_{\text{gap}} = 40 \text{ nm}$. The coupling loss exhibits its minimum value at $h_{\text{Si}} = 200 \text{ nm}$. When $h_{\text{Si}} > 200 \text{ nm}$, the side lobes of the Si-wire waveguide are too far from the MIM waveguide, thereby reducing the coupling efficiency. On the other hand, when $h_{\text{Si}} < 200 \text{ nm}$, the optical mode in the Si-wire waveguide is spread out, thereby reducing the coupling efficiency.

Fig. S4. Coupling losses for various Si-wire heights.