

Compact and highly efficient plasmonic mode conversion in a metal slab waveguide with asymmetric subwaveguides

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Compact plasmonic devices have paved a way to achieve highly integrated photonic circuit for the next-generation information technology. In this Letter, we proposed compact and highly efficient plasmonic mode conversion between symmetric and antisymmetric modes in metal slab waveguides containing asymmetric dielectric substructures. We derived intuitive analytical formulations concerning the mode asymmetry and intermode coupling in the asymmetric subwaveguide. And we estimated a conversion efficiency and compactness of the proposed plasmonic mode conversion. As a result, we confirmed the compact and high-efficiency plasmonic mode converter with conversion efficiency as high as 90% and a compact size up to one wavelength. The suggested device will give us potential possibilities to construct on-chip photonic computing networks.

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Nowadays, vast research and development on plasmonic devices such as plasmonic switch, modulators, and sensors, have guaranteed the next-generation information technology based on integrated photonic circuits [1–3]. Here, metal slab waveguides are considered as one of the most simple and ideal elements, where two modes exist: symmetric (long-range) and antisymmetric (short-range) modes, which have the wide range of applications in biosensors and optical integrated circuits [3–5]. However, the excitation of those modes in the metal slab waveguides has a bit of technical difficulties. For example, the asymmetric modes are difficult to be excited by efficient configuration such as end-fire coupling and tapered dielectric junctions because of their antisymmetric lateral field intensity distribution [2]. Therefore, mode conversion between those modes can further more effectively enhance the practicability of plasmonics.

The paradigm of the conversion is mostly based on an intermode coupling by symmetry breaking of dielectric environment [6–16]. The symmetry breaking can be attained by built-in structural asymmetry such as a specific cavity [7,8] and a grating [9], or by varying path length or dielectric medium [10–16]. Also, it can be realized by actively induced alternation of dielectric environment [17] based on electro-optical [14,18,19], magneto-optical [16,20–24], thermo-optical [25,26], nonlinear optical and photorefractive effects [27–30], or by controlling chemical potential of graphene [31], and implanting ions [32,33] and by varying carrier density [34–36]. Recently, researchers have suggested a high-efficiency plasmonic mode conversion using magneto-optical effect [16] and a compact plasmonic device for mode

conversion based on two-wire transmission line (TWTL) configuration [13] and graphene parallel plate waveguides in midrange infrared regions [31].

Nevertheless, the combination of high efficiency with compactness in metal slab waveguides has not been addressed much. Generally, the extent of actively induced dielectric manipulation is too small to provide the sufficient intermode coupling for mode conversion within a compact size of device [17–30,32–36]. Thus, those converters usually have a length of tens of wavelength [6–12,14–16]. On the other hand, compact plasmonic converters have not provided high efficiency. For example, a mode converter using a TWTL configuration, with a conversion efficiency of up to 35% [13].

In this paper, we studied on plasmonic mode conversion between symmetric and antisymmetric modes in a metal slab waveguide with an asymmetric dielectric environment. We derived intuitive analytical formulations concerning the mode asymmetry and modulation by intermode coupling in the asymmetric subwaveguide. The analytical study leads us to suggest a compact plasmonic mode converter. We confirmed the function of mode conversion numerically and estimated the conversion efficiency and the compactness of the plasmonic mode converter according to the extent of dielectric asymmetry. As a result, we revealed that our converter has a conversion efficiency as high as 90% and a compact size up to a wavelength. The suggested device will give us potential possibilities to achieve highly integrated photonic interconnect and network.

Lets consider plasmon modes propagating in the structure as shown in Fig. 1(a), where a metal film is surrounded by two dielectric layers with different dielectric permittivity. In two cases, the permittivity differences between the two dielectric layers are all $\Delta\epsilon$. For the fundamental TM mode, we can obtain a dispersion relation from Maxwell equation and boundary conditions as follows [2]:

$$e^{-t/\delta} = \frac{q_m + q_1}{q_m - q_1} \frac{q_m + q_2}{q_m - q_2}, \quad (1)$$

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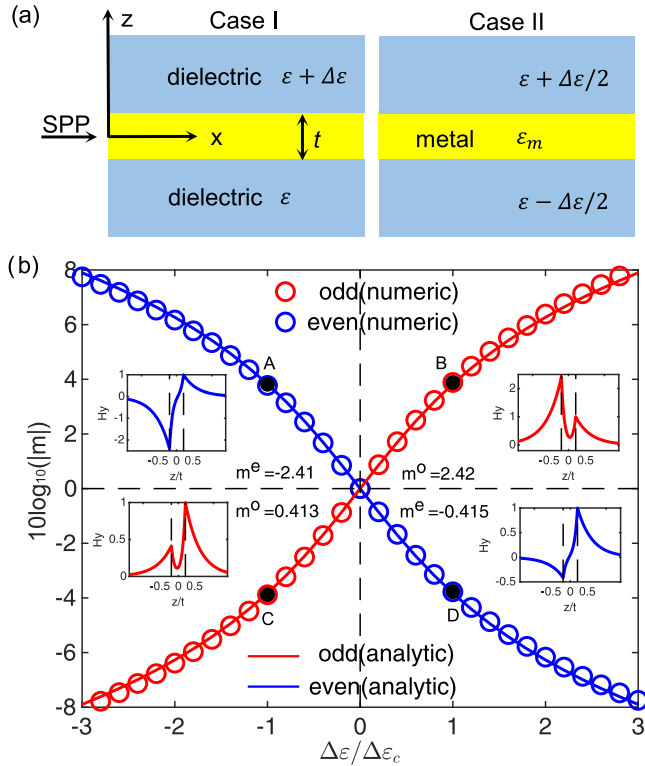


FIG. 1. (a) The configuration of asymmetric metal slab waveguides. (b) Mode asymmetry of odd and even mode according to normalized permittivity difference in the asymmetric waveguide as shown in (a), with $t = 100$ nm at $\lambda = 800$ nm. The solid curves are by Eq. (4) and the circles are by numerical solutions of Eq. (2). Insets show the mode profile of odd and even modes at points of A, B, C, and D.

where $q_m = k_m/\varepsilon_m$, $k_m^2 = \beta^2 - k_0^2\varepsilon_m$, $k_0 = 2\pi/\lambda$ is the vacuum wavenumber, λ is the incident wavelength, δ is the skin depth defined as $\delta = 1/2 k_m$, t is the thickness of the metal film, β is the propagation constant, ε_m is the permittivity of the metal, and ε is the permittivity of the dielectric substrate. We assumed the following relations. For case I, $q_1 = k_1/(\varepsilon + \Delta\varepsilon)$, $q_2 = k_2/\varepsilon$, $k_1^2 = \beta^2 - k_0^2(\varepsilon + \Delta\varepsilon)$, $k_2^2 = \beta^2 - k_0^2\varepsilon$ and for case II, $q_1 = k_1/(\varepsilon + \Delta\varepsilon/2)$, $q_2 = k_2/(\varepsilon - \Delta\varepsilon/2)$, $k_1^2 = \beta^2 - k_0^2(\varepsilon + \Delta\varepsilon/2)$, $k_2^2 = \beta^2 - k_0^2(\varepsilon - \Delta\varepsilon/2)$.

From the dispersion relation (1), we can get solutions for two modes: odd and even modes. These modes are called the symmetric and antisymmetric modes in the symmetric structure without $\Delta\varepsilon$. However, $\Delta\varepsilon$ induces an asymmetry of the mode profile. We define a degree of the mode asymmetry as follows:

$$m = \frac{H_y(z = -t/2)}{H_y(z = t/2)}, \quad (2)$$

where $H_y(z = -t/2)$ and $H_y(z = t/2)$ are the magnetic field component at the bottom and top interfaces of the structure in Fig. 1(a), respectively. From the continuity of the field component at the interfaces [2], the mode asymmetry can be

expressed as follows:

$$m = \frac{q_m + q_1}{q_m - q_2} e^{t/2\delta}. \quad (3)$$

Lets assume that the metal film thickness t is much larger than the skin depth δ . And if we assume $\Delta\varepsilon \ll \varepsilon$, we can get an analytical expression for the mode asymmetry as follows:

$$m^{o(e)} \approx (-)^{\sqrt{1 + (\Delta\varepsilon/\Delta\varepsilon_c)^2}} + \Delta\varepsilon/\Delta\varepsilon_c, \quad (4)$$

$$\Delta\varepsilon_c = \frac{8\varepsilon^2}{\varepsilon - \varepsilon_m} e^{-t/2\delta},$$

where the superscripts o and e represent the odd and even modes, respectively, and $\Delta\varepsilon_c$ is a characteristic permittivity difference. Here, we note that $\Delta\varepsilon = \pm\Delta\varepsilon_c$ corresponds to $m^o = \sqrt{2} \mp 1$.

From formula (4), we can see an interesting relation as follows:

$$m(\Delta\varepsilon) \cdot m(-\Delta\varepsilon) = 1, \quad (5)$$

$$m^o(\Delta\varepsilon) \cdot m^e(\Delta\varepsilon) \approx -1.$$

Figure 1(b) shows the mode asymmetry for the odd (red curves) and even (blue curves) modes with respect to $\Delta\varepsilon$ normalized by $\Delta\varepsilon_c$ in the structure of Fig. 1(a), with $t=100$ nm at $\lambda = 800$ nm. Here we assumed that $\varepsilon = 6.25$. The experimental data for the permittivity of silver [37] are used as ε_m . As shown in this figure, the analytical results from Eq. (4) (solid curves) agree well with the numerical results using Eq. (2) (circles), which are obtained by the finite element method with software COMSOL Multiphysics. This figure confirms the relation (5). Insets show the asymmetric mode profile of odd and even modes when $\Delta\varepsilon = \pm\Delta\varepsilon_c$ corresponding to points A–D.

Next, based on the concept of mode asymmetry, we focused on a coupling between waveguide modes during its propagation in the structure as shown in Fig. 2(a). Compared to the case of Fig. 1(a), the structure consists of two waveguides with symmetry and asymmetry in its dielectric environment. If we assume that the symmetric (antisymmetric) SPP mode is incident through the symmetric domain, at the boundary between two domains, the incident mode is expanded to a linear combination of odd and even modes of the asymmetric domain,

$$H_y(x, z) = c_1 H_y^o(z) \exp(i\beta^o x) + c_2 H_y^e(z) \exp(i\beta^e x). \quad (6)$$

From the continuity of field distribution at the boundary and Eq. (3), one can obtain the following relation for the expansion coefficients, c_1 and c_2 :

$$\frac{c_2}{c_1} \approx \frac{(m^o - p)m^o}{pm^o + 1} \exp\left[\frac{(k^e - k^o)t}{2}\right], \quad (7)$$

where $p = 1$ for a symmetric incident mode and $p = -1$ for an antisymmetric one.

During propagation of SPP along the waveguide, the lateral field distribution in the z direction varies due to difference in propagation constants between the odd and even modes $\Delta\beta$ ($=\beta^e - \beta^o$). If we remind the assumption $t \gg \delta$ and $\Delta\varepsilon \ll \varepsilon$, $\Delta\beta$ can be approximately expressed as follows, in

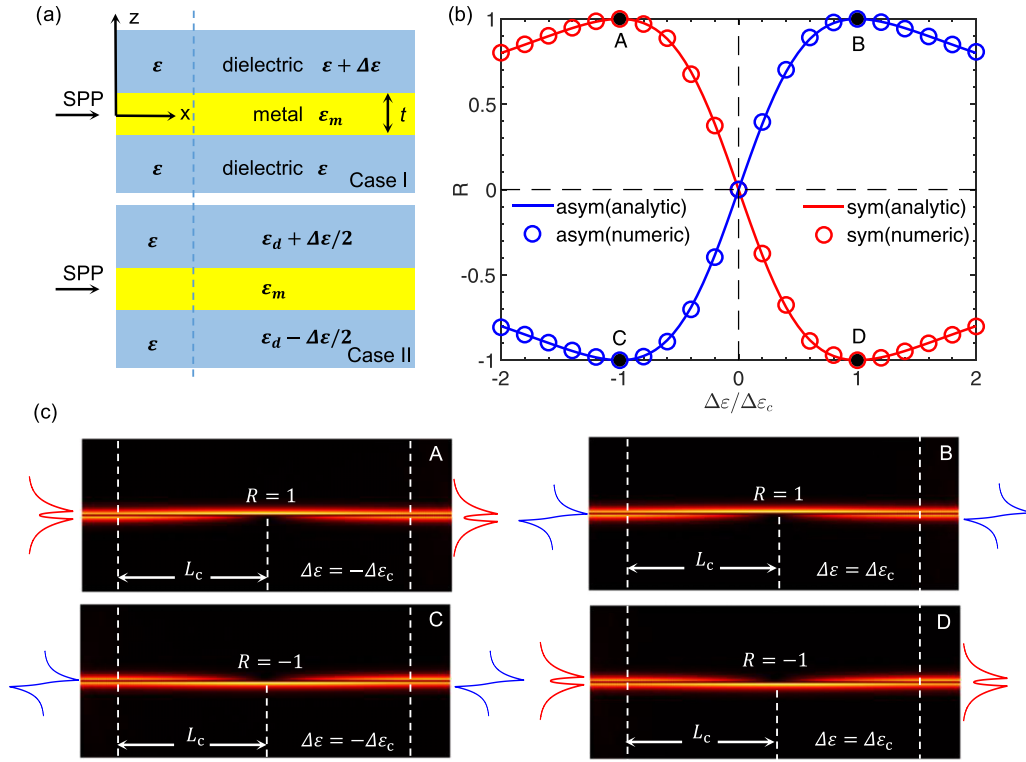


FIG. 2. (a) The scheme of a metal slab waveguide for plasmonic mode modulation. It consists of two domains with symmetric and asymmetric structures. (b) The field intensity contrast R between the interfaces of the waveguide of (a) according to $\Delta\epsilon$. The red and blue color represents the symmetric and antisymmetric incident mode, respectively. The solid line shows the analytical results from Eq. (10) and the circles are the numerical result based on simulation. (c) Numerical simulation plot for distributions of $|H_y|^2$ corresponding to points A–D in (b). Here, the value of $\Delta\epsilon_c (= 0.063)$ is calculated by Eq. (4). Other parameters are the same as in Fig. 1. We did not consider the waveguide loss for intuition.

an analogous manner to the derivation in the Supplemental Material of Ref. [22],

$$\Delta\beta \approx 2\sqrt{\Delta\beta_o^2 + \Delta\beta_\delta^2},$$

$$\Delta\beta_o = -2\frac{\epsilon_m\epsilon}{\epsilon_m^2 - \epsilon^2}e^{-t/2\delta}\beta_o, \quad \Delta\beta_\delta = \frac{1}{4}\frac{\epsilon_m}{\epsilon + \epsilon_m}\frac{\Delta\epsilon}{\epsilon}\beta_o, \quad (8)$$

where $\beta_o = \sqrt{\epsilon\epsilon_m/(\epsilon + \epsilon_m)}k_0$ is the propagation constant in dielectric/metal single interface, $\Delta\beta_o$ is an intrinsic difference in the wavenumber between the odd and even modes in the symmetric waveguide ($\Delta\epsilon = 0$), and $\Delta\beta_\delta$ is an additional difference due to the permittivity difference $\Delta\epsilon$. Here, we note that $|\Delta\beta_o| = |\Delta\beta_\delta|$ in a special case when $\Delta\epsilon = \pm\Delta\epsilon_c$.

Now, we define a field intensity contrast R between the dielectric/metal interfaces as follows:

$$R = \left(\frac{|H_y(x, z = \frac{t}{2})|^2 - |H_y(x, z = -\frac{t}{2})|^2}{|H_y(x, z = \frac{t}{2})|^2 + |H_y(x, z = -\frac{t}{2})|^2} \right)_{\max}. \quad (9)$$

At a propagation length $L = \pi/Re\Delta\beta$, the field contrast R is simplified as a following form from Eqs. (4) and (6)–(8):

$$R^{(s)a} = (-)\frac{2\Delta\epsilon/\Delta\epsilon_c}{1 + (\Delta\epsilon/\Delta\epsilon_c)^2}, \quad (10)$$

where the superscripts s and a represent symmetric and antisymmetric incident modes, respectively. From Eq. (10), the contrast R becomes its extreme value ± 1 when $\Delta\epsilon = \pm\Delta\epsilon_c$.

Here, $R = 1$ means that the optical field is concentrated into the upper interface of the waveguide whereas $R = -1$ means that the field is concentrated into the under interface of the waveguide. Equation (10) implies another important relationship as follows:

$$R(\Delta\epsilon) = -R(-\Delta\epsilon), \quad R^a = -R^s. \quad (11)$$

Figure 2(b) shows the field intensity contrast R with respect to the normalized $\Delta\epsilon$. The red color represents the symmetric SPP mode and the blue color represents the antisymmetric mode. The analytical results (solid lines) are calculated by Eq. (10) and circles are numerical results. Here, the value of $\Delta\epsilon_c (= 0.063)$ is calculated by Eq. (4). Figure 2(c) shows the numerical results of distribution of $|H_y|^2$ for the points A–D in (b). From this figure, one can find that the field distribution of A and B, C and D are very similar, respectively. If one combines the structures A and B or C and D at the extreme contrast point ($R = \pm 1$), incident modes would be converted to another mode. That's how one can achieve a mode conversion.

At the value of $\Delta\epsilon_c$, a characteristic propagation length L_c for the high contrast are obtained as follows:

$$L_c \approx \frac{\sqrt{2}}{16}(\epsilon - \epsilon_m)\left(\frac{\epsilon + \epsilon_m}{\epsilon\epsilon_m}\right)^{3/2}e^{t/2\delta}\lambda. \quad (12)$$

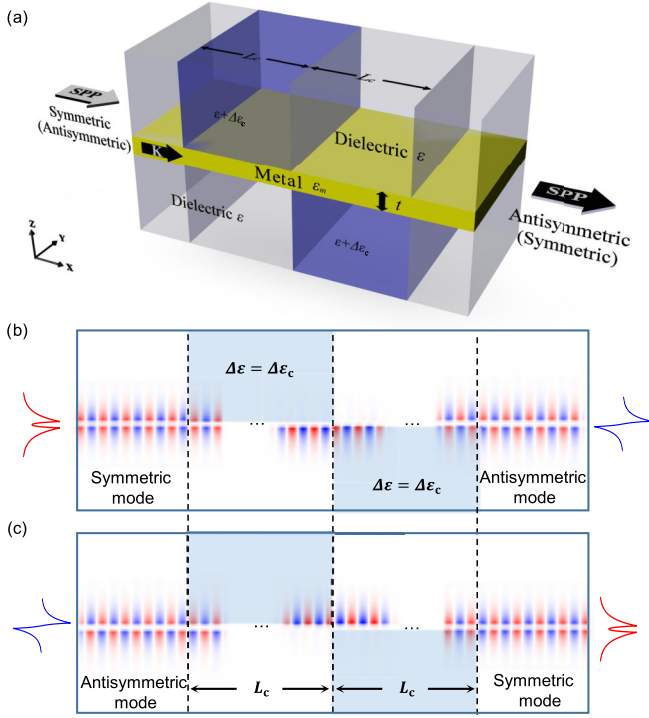


FIG. 3. Plasmonic mode conversion in a metal slab waveguide with asymmetric subwaveguides. (a) Scheme of the mode converter. The process of symmetric/antisymmetric mode conversion (b) and antisymmetric/symmetric mode conversion (c). Here $L_c = 16.0 \mu\text{m}$ and $\Delta\epsilon_c = 0.063$ have been calculated by Eq. (4) and Eq. (12). Other parameters are the same as in Fig. 1. We did not consider the waveguide loss for intuition.

From Eq. (4) and Eq. (12), $\Delta\epsilon_c = 0.063$ and $L_c = 16.0 \mu\text{m}$ if we assume that $t = 100 \text{ nm}$, $\lambda = 800 \text{ nm}$, $\epsilon = 6.25$, and the metal is silver. In the case of $t = 110 \text{ nm}$, $\Delta\epsilon_c = 0.038$ and $L_c = 26.6 \mu\text{m}$. We note that such a minor permittivity difference $\Delta\epsilon_c$ can be induced by active controls such as thermo-optical, electro-optical, and photorefractive effect.

From these results and Eqs. (4) and (12), we can obtain a following trade-off relation between $\Delta\epsilon_c$ and L_c ,

$$L_c \cdot \Delta\epsilon_c \approx \frac{\sqrt{2}}{2} \epsilon^{1/2} \left(\frac{\epsilon + \epsilon_m}{\epsilon_m} \right)^{3/2} \lambda. \quad (13)$$

When $\lambda = 800 \text{ nm}$ and $\epsilon = 6.25$, the above relation (13) is simplified to $L_c \cdot \Delta\epsilon_c \approx 1 (\mu\text{m})$. The relation implies that one can achieve a compact plasmonic mode conversion device if one can introduce a large dielectric asymmetry. Such a big dielectric difference can be implemented by simply changing one of dielectric mediums or by using a large refractive index modulation method based on carrier density modification [34,35].

Based on the analytical study, we suggested a compact plasmonic mode converter. The configuration is shown in Fig. 3(a). It has an asymmetric waveguide link which consists of two subwaveguides with reverse asymmetry of each other. Each subwaveguide has a length of L_c and a dielectric asymmetry $\Delta\epsilon_c$. The input SPP mode is incident to the left port of the converter, and the converted mode is outputted to the right port. Figures 3(b) and 3(c) show the conversion process of the mode converter. As can be seen here, the incident symmetric mode is sufficiently converted to the antisymmetric output mode, and vice versa.

Figure 4 shows the compactness and efficiency of the suggested plasmonic mode converter. In Fig. 4(a), one can see characteristic length L_c and permittivity difference $\Delta\epsilon_c$, which represent the size of the mode converter and dielectric asymmetry, according to the thickness of metal film t . Figure 4(b) shows a trade-off relation between L_c and $\Delta\epsilon_c$. From this relation, we anticipated that one can demonstrate a compact mode converter with the size of up to one wavelength in an asymmetric structure with a sufficient dielectric asymmetry up to one. In Fig. 4(c), we estimated the efficiency of the suggested converter. As can be seen, the converting efficiency is more than 95% from 780 nm to 820 nm, and more than 80% in a wide band from 750 nm to 850 nm, independent of the device size. These results guarantee a high efficiency and broadband characteristics of the converter. Here, the conversion efficiency η is calculated as a percentage

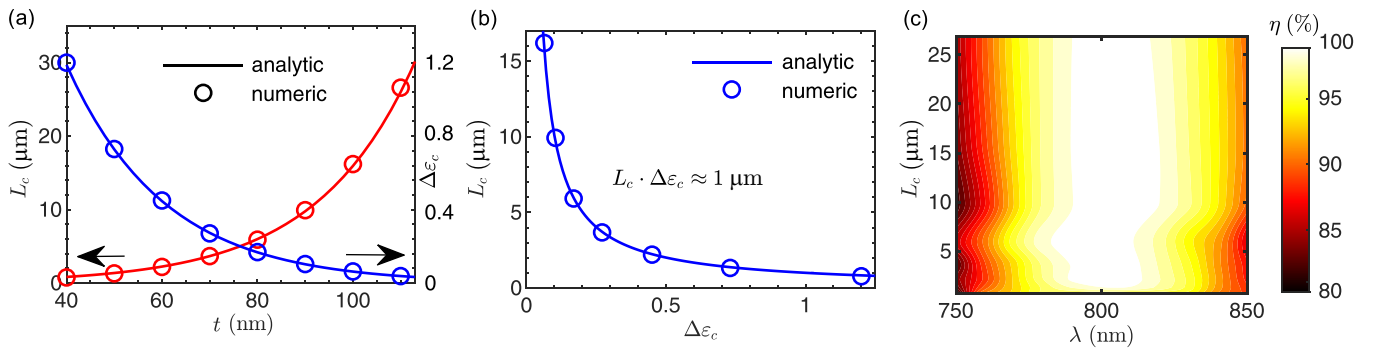


FIG. 4. Compactness and efficiency of the suggested plasmonic mode converter. (a) Characteristic length L_c and permittivity difference $\Delta\epsilon_c$ according to the thickness of metal film t . (b) Trade-off relation between L_c and $\Delta\epsilon_c$. Here, analytical results are obtained by Eqs. (4), (12), and (13), and numerical results (circles) are based on simulation. And the incident wavelength $\lambda = 800 \text{ nm}$. (c) The efficiency of the suggested plasmonic mode converter with respect to its size represented by L_c and the incident wavelength λ . Here, L_c are the calculated values for $\lambda = 800 \text{ nm}$.

of the targeted mode in the intensity of the output field, so that it isn't affected by the waveguide loss. The insertion loss is about 10 dB (a transmission of 10%) for the case of $L_c = 16 \mu\text{m}$ as in Fig. 3 and can be dramatically reduced to less than 1 dB (a transmission of more than 80%) for the compact case of $L_c = 1 \mu\text{m}$, that is, the more compact size of the converter is the smaller waveguide loss. Moreover, the loss does not influence the efficiency because the intensity reduction due to the absorption occur in both modes in the output field.

In conclusion, we proposed a plasmonic mode conversion between symmetric and antisymmetric modes in a metal slab waveguide with an asymmetric dielectric environment and discussed its compactness and efficiency. We derived intuitive analytical formulations concerning the mode asymmetry and

intermode coupling in the asymmetric waveguide. The theoretical study enables us to suggest a high-performance mode conversion using the plasmonic modulation through the intermode coupling. We showed a high-efficiency mode conversion more than 90% within a wideband of wavelength. Also, we confirmed a compactness of the plasmonic mode converter with a size of even one wavelength in an asymmetric structure with a sufficient dielectric asymmetry up to one. The suggested device will provide us a potential candidate to achieve highly integrated photonic interconnect and network.

There are no conflicts of interest to declare.

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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