Efficient coupling of light from dielectric to HIMI plasmonic waveguide

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This is the first report on the investigation of a hybrid plasmonic tapered coupler injecting light efficiently from conventional dielectric waveguide to a hybrid insulator–metal–insulator (HIMI) plasmonic waveguide. The proposed structure gives high transmission efficiency and suppresses the reflection losses significantly. With this tapered coupling mechanism, maximum transmittance and return loss of 98% and 26 dB have been observed, respectively. The coupler also offers very good propagation length (274 µm) along with minimal mode propagation losses (0.016 dB/µm). Apart from that, it offers decent confinement of light in low dielectric regions up to 32%. The proposed structure is designed in an ultra-short tapered length of 1.0 µm, and the entire structure occupies a footprint area of $1.4 \times 2.4\ \mu m^2$. Proposed hybrid waveguide coupler could be useful for several chip scale applications.

1. Introduction: In modern technology, plasmonic devices play an essential role in optical communication due to their compact size compared to conventional photonics. Plasmonic waveguides and components are promising as they can break the diffraction limit unlike the photonics devices [1]. Till date, several plasmonic waveguides have been reported such as metal slot, metal wedge, grating, metal–insulator etc. Also, there are other types of waveguides that have been studied such as finite thickness MIM and asymmetric MIM having different metal layers [2–4]. Besides, in [4] a MIM plasmonic waveguide of ultrahigh figure of merit is reported, it employs two dissimilar metals. Thus broadly speaking there are two major types of plasmonic waveguides, i.e. insulator–metal–insulator (IMI) and metal–insulator–metal (MIM), which are used for several applications. These two plasmonic waveguides suffer from many limitations such as IMI plasmonic waveguide offers good propagation length but poor light confinement. Contrary to this, MIM plasmonic waveguide offers very tight confinement but suffers from huge ohmic losses [5]. To overcome these limitations, modern technology is adopting hybrid structures of plasmonic waveguides which shows a remarkable improvement in waveguide performance. The hybrid plasmonic waveguide may be divided into three categories such as hybrid metal–insulator (HMI) for moderate performance, hybrid MIM (HMIM) for tight confinement and hybrid IMI (HIMI) for larger propagation length [1, 5, 6]. HIMI plasmonic waveguide offers least ohmic losses among all kinds of plasmonic waveguides, which makes it more suitable for coupler design.

Hence in this Letter, we propose HIMI plasmonic waveguide tapered coupler, which couples light from a broad (µm) dielectric waveguide input to a narrow (nm) HIMI plasmonic waveguide output [7].There are many methods for light coupling to plasmonic waveguides such as grating coupler [8], prism coupler [9], evanescent coupler [10], tapered coupler [11] etc. However, in this work, we demonstrate a tapered coupler which gradually transforms propagation mode from micrometre to nanometre size thus efficiently coupling light from conventional dielectric to hybrid plasmonic structure. For the proposed tapered HIMI coupler, all important parameters such as propagation length (L_{prop}), mode propagation loss, transmittance, reflection losses and confinement etc. have been calculated. We have analysed coupler performance by several parametric variations of the proposed structure such thickness of various layers, taper length, modal conversion etc. Further coupler efficiency has also been observed by designing dielectric to dielectric (DtD) coupler, in which coupling between two dielectric waveguides is achieved via tapered plasmonic coupler. The proposed design outperforms previous reported works in several aspects such as transmission and loss characteristics, size etc. [12, 13]. The proposed coupler could offer compact integration between the silicon photonics and hybrid plasmonic, which may be useful for several chip scale applications [14, 15].

2. Modelling and simulation method: Top view of the proposed multilayer tapered coupler along with multilayer HIMI plasmonic output waveguide and input dielectric slab waveguide is shown in Fig. 1*a*. Cross-section view of input dielectric slab waveguide is shown in Fig. 1*b*, which uses Si and SiO_2 as dielectric materials with refractive indices 3.5 and 1.44, respectively [6]. For the HIMI plasmonic waveguide as shown in Fig. 1*c*, silver (Ag) is used as the metal film. The metal film is sandwiched between a set of dielectrics (Si–SiO_2) as shown in Fig. 1*c* [6]. The permittivity of silver is defined by Drude model as

$$\varepsilon_m = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + j\omega\Gamma}$$

where $\varepsilon_\infty = 1$ is dielectric constant at the infinite angular frequency, $\omega_p = 1.39 \times 10^{16}$ rad/s is the bulk plasma frequency and $\Gamma = 3.08 \times 10^{13}\ s^{-1}$ is the damping frequency of oscillation [16]. At 1.55 µm operating wavelength, the permittivity of silver is calculated as $\varepsilon_m = 129 + 3.33i$. Silica and air are used for substrate and cladding, respectively. Light is coupled from input dielectric to output HIMI plasmonic waveguide with the help of HIMI tapered coupler, as shown in Fig. 1*a*. Parameters of the structure are set as the width of the Si in the dielectric slab $W_1 = 1.0$ µm, width in the HIMI plasmonic waveguide $W_2 = 0.25$ µm and thickness of silica, silver and silicon are $t_s = 0.02$ µm, $t_m = 0.03$ µm, and $t_h = 0.25$ µm, respectively, as shown in Figs. 1*a*–*c*. $L_d = 0.8$ µm, $L_t = 1.0$ µm, $L_p = 0.6$ µm designate the lengths of the dielectric slab, taper and plasmonic waveguide, respectively. All simulations are performed using frequency domain solver of CST microwave studio suite, which is a comprehensive 3D electromagnetic tool. For achieving accurate results, perfectly matched layer boundary conditions are applied and 25 tetrahedrons per wavelength are used for the refined meshing of structure.

Fabrication of proposed coupler may be done by some standard semiconductor fabrication methods. Different layers may be deposited by plasma enhanced chemical vapour deposition, oxidation,

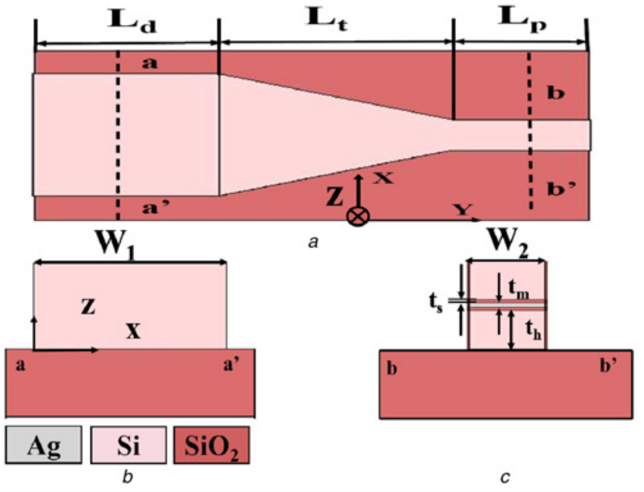

Fig. 1 *Construction dimensions*
a Top view of coupler along with input dielectric and output HIMI plasmonic waveguide
b Cross-section views of input dielectric waveguide
c Cross-section views of output HIMI plasmonic waveguide

and metallisation processes. Then waveguide patterning to typical nanometre dimensions may be done using E-beam lithography. Unwanted metal and dielectric layers may be etched out using reactive ion etching [17, 18].

3. Result and discussion

3.1. HIMI plasmonic waveguide: Propagation length ($L_{prop} = 1/2\alpha$, where α is attenuation constant) and mode propagation losses (M.L. $= -10\log_{10}(1/e)/L_{prop} \approx 4.343/L_{prop}$)) [1] of HIMI plasmonic waveguide have been presented in Fig. 2*a*. Propagation length increases on increasing both, i.e. high dielectric and low dielectric thicknesses, as shown in Fig. 2*a*. Losses follow the reverse trend of propagation length and it reduces on increasing both dielectric thicknesses, as less energy overlaps with metal film. Propagation length and M.L. of 253 µm and 0.017 dB/µm have been observed at 1.55 µm wavelength, which are way better than previous reports [12, 13]. Fig. 2*b* shows the impact of the silica layer thickness t_s and the dielectric thickness t_h on the confinement factor ($\Gamma = E_{mode}/E_{total}$, where E_{mode} is the mode area energy in spacer layers and E_{total} is the total energy of excitation) [5]. It is observed from Fig. 2*b* that the maximum confinement factor of 46% has been achieved for silica thickness 0.05 µm and dielectric cladding thickness of 0.25 µm, respectively. Though we achieve very good performance, i.e. P.L. and confinement at higher value of low dielectric, i.e. 0.05 µm, but it increases mode size also, as shown in Fig. 2*b*, which is not desirable. Moreover at higher value of low dielectric, the plasmonic and dielectric modes get decoupled, which is not desirable. Hence we optimise $t_s = 0.02$ µm and $t_h = 0.25$ µm, for proper balance between mode size and losses.

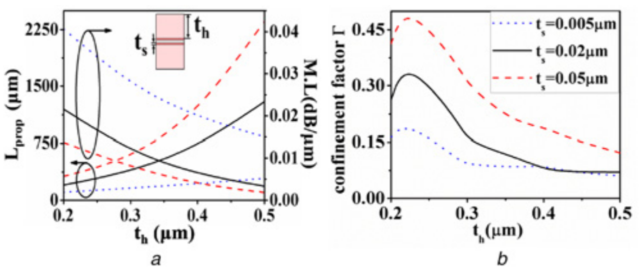

Fig. 2 *HIMI plasmonic waveguide*
a L_{prop} and mode propagation loss
b Confinement factor at $t_h = 0.2$–0.5 µm and $t_s = 0.005$, 0.02, 0.05 µm

At these values confinement factor of 38% has been achieved. In Figs. 3*a–c*, E-field distributions at different spacer thicknesses 0.005, 0.02 and 0.05 µm are shown, respectively. This clearly depicts that at a low value of spacer thickness, HIMI plasmonic waveguide supports predominantly plasmonic modes as shown in Fig. 3*a*. On further increasing the thickness, dielectric mode evolves and its coupling with plasmonic mode results in hybrid plasmonic mode propagation, as shown in Fig. 3*b*. On further increasing the thickness, dielectric mode dominates as shown in Fig. 3*c*.

3.2. Dielectric to HIMI plasmonic tapered coupler: To couple light in HIMI plasmonic waveguide, firstly light is launched into the dielectric slab waveguide, and its mode evolution is shown in Fig. 4*a* (*i–iii*). The optical energy is well confined in the dielectric waveguide supporting dielectric mode which couples light to the HIMI plasmonic waveguide via tapered structure. The taper structure gradually transforms the micron size dielectric mode to the nano size plasmonic mode as evident from 2D E-field distribution shown in Fig. 4*b*.

It is clearly visible from Fig. 4*b* that there are sharp peaks of E-fields in spacer regions of HIMI plasmonic waveguide, contrary to this input dielectric slab waveguide gives elliptical profile.

The parameters of proposed taper HIMI plasmonic coupler are already defined in Section 2, which are optimised by several parametric variations for optimal performance. Percentage transmission (P_{out}/P_{in}) along with return loss ($10\log_{10}(P_{out}/P_{in})$) [19] have been plotted in wavelength range 1.50–1.58 µm, as shown in Fig. 5. Transmittance and return loss of 98% and 26 dB have been found, respectively, which are better than previous reports [12, 13].

Coupler shows broadband behaviour, as it gives very good performance for whole band. A 3D E-field view is also shown in inset of Fig. 5, which shows transition from dielectric to plasmonic modes.

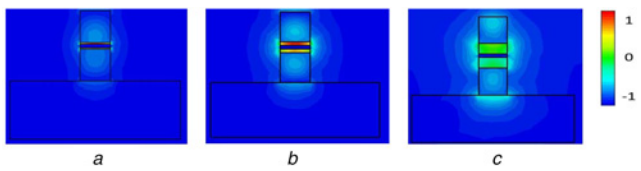

Fig. 3 *E-field distribution for various silica thickness at the wavelength of 1.55 µm*
a $t_s = 0.005$ µm
b $t_s = 0.02$ µm
c $t_s = 0.05$ µm

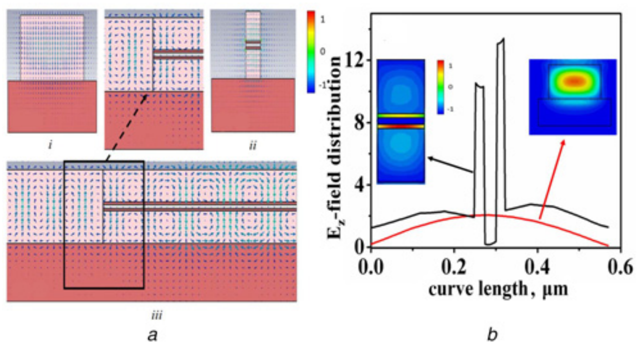

Fig. 4 *E-field profile*
a Normalised E-field profile for (at 1.55 µm) *i*. dielectric waveguide, *ii*. plasmonic waveguide and *iii*. dielectric to plasmonic waveguide along the length
b E_z-field profile of dielectric waveguide input and HIMI plasmonic waveguide output at 1.55 µm

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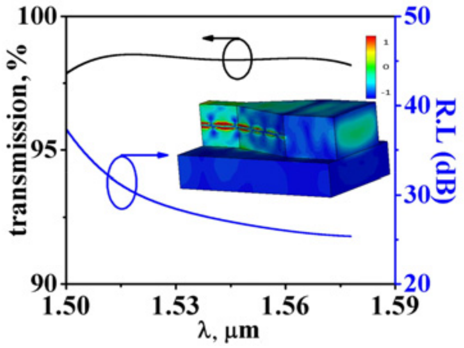

Fig. 5 *Transmission and return loss (R.L.) for HIMI taper coupler with the optimised parameter ($W_1 = 1.0\,\mu m$, $W_2 = 0.25\,\mu m$, $t_m = 0.03\,\mu m$, $t_s = 0.02\,\mu m$, $L_d = 0.8\,\mu m$ $L_t = 1.0\,\mu m$ and $L_p = 0.6\,\mu m$)*

Next, we investigate the performance of dielectric to plasmonic coupler at 1.55 μm wavelength using parametric variations.

Firstly coupler has been analysed at different spacer layer thickness as shown in Figs. 6*a* and *b*. Transmission efficiency is highly sensitive to silica layer thickness, as shown in Fig. 6*a*. It increases slightly first and then reduces with t_s. At the low value of t_s, proposed coupler waveguide acts as a standard plasmonic waveguide, hence suffers from severe ohmic losses, which results in reduction of transmission efficiency [6]. Proposed coupler offers poor transmission efficiency at larger spacer thickness also, due to weaker confinement in dielectric mode. Highest transmission of 98% is achieved at intermediate thickness (0.02 μm) only, where hybrid modes arrive. In order to further characterise the dispersion and loss behaviour of the coupler, we have calculated real ($\mathrm{Re}(N_{\mathrm{eff}}) = \beta/k_0$, here β and k_0 are phase constant and wave number, respectively) and imaginary part ($\mathrm{Imag}(N_{\mathrm{eff}}) = \alpha/k_0$) of effective refractive indices, respectively, as shown in Fig. 6*b*. $\mathrm{Re}(N_{\mathrm{eff}})$ shows the dispersion properties and $\mathrm{Imag}(N_{\mathrm{eff}})$ is responsible for the losses [1]. As evident $\mathrm{Imag}(N_{\mathrm{eff}})$ reduces with increasing thickness of spacer silica layer, as shown in Fig. 6*b*.

Next, we investigate the coupler performance with respect to metal thickness at the optical wavelength of 1.55 μm. The transmission with respect to metal thickness has been calculated in Fig. 7*a*, it is found that the transmission increases first and then reduces on increasing the metal thickness. Maximum transmission of 98% has been achieved at an optimal value, i.e. 0.03 μm metal thickness. $\mathrm{Re}(N_{\mathrm{eff}})$ and $\mathrm{Imag}(N_{\mathrm{eff}})$ have also been plotted with metal thickness in Fig. 7*b*. $\mathrm{Re}(N_{\mathrm{eff}})$ decreases and $\mathrm{Imag}(N_{\mathrm{eff}})$ increases with metal thickness which means that the confinement of light decreases and losses increases due to an increase in metal portion.

Next, we investigate the coupler performance with respect to the length of the tapered section (L_t) and length of HIMI section (L_p) as shown in Figs. 8*a* and *b*.

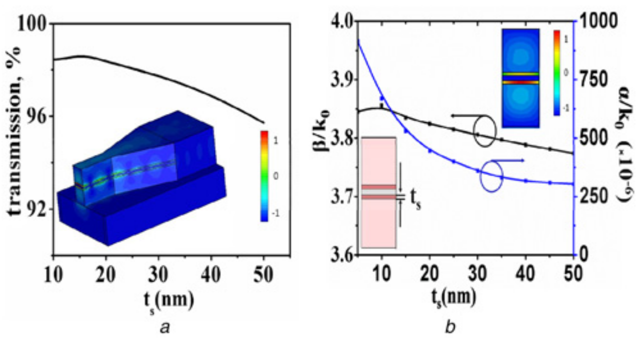

Fig. 6 *Transmission of coupler and dispersion relation with respect to t_s*
a Transmission of HIMI taper coupler with respect to silica thickness
b Normalised phase and attenuation constants with respect to silica thickness

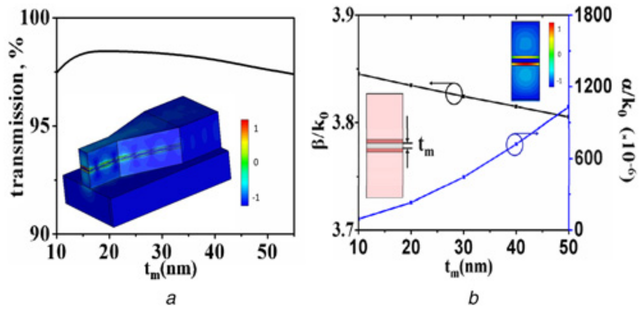

Fig. 7 *Transmission of coupler and dispersion relation with respect to t_m*
a Transmission of HIMI taper coupler
b Normalised phase and attenuation constants with respect to silver thickness

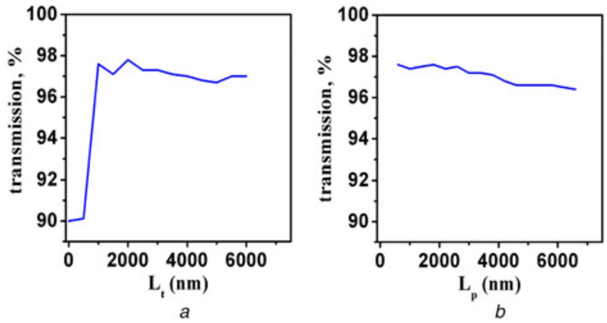

Fig. 8 *Transmission of HIMI taper coupler*
a With respect to tapered length (L_t)
b With respect to length of HIMI waveguide (L_p)

Without tapered section, the transmission is 90% but as the length of the tapered section is increased the transmission also increases becoming optimum at $L_t = 1.0\,\mu m$. With respect to the length of HIMI section the transmission is not so sensitive as expected, though it decreases slightly on increasing the length of the section. This is due to the fact that ohmic loss increases.

3.3. Analysis of DtD coupler: To assess the effectiveness of the proposed coupler as an interconnect between dielectric and plasmonic components, two HIMI taper couplers are connected back-to-back to realise a DtD coupler as shown in the inset of Fig. 9. First input is given to the dielectric slab waveguide, where dielectric modes get excited, then it is connected to the HIMI plasmonic

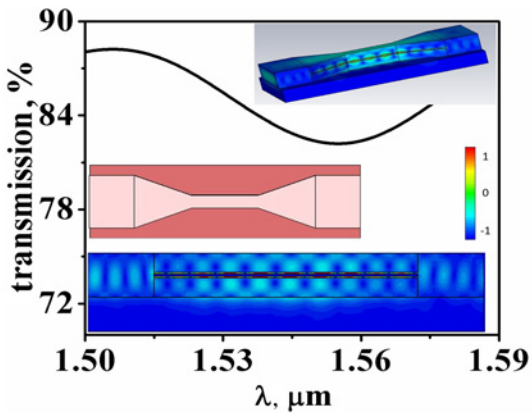

Fig. 9 *Transmission of the DtD coupler at wavelength range of 1.50–1.59 μm with the E-field distribution of the DtD coupler along the length at the wavelength of 1.55 μm*

taper waveguide in which hybrid plasmonic modes get excited. Finally, the light gets decoupled back to the dielectric waveguide from HIMI plasmonic waveguide. For the proposed DtD coupler, 82% coupling has been achieved at 1.55 μm wavelength, as shown in Fig. 9. E-field distribution in the coupler at the wavelength of 1.55 μm is also shown in the inset of Fig. 9, which clearly shows the transition that how dielectric modes are converted into plasmonic and then back to dielectric. The total footprint area of this DtD coupler is only $1.4 \times 4.8\ \mu m^2$.

4. Conclusion: In conclusion, we have designed a HIMI tapered coupler which has a very good transmission. The coupler can efficiently inject light energy from the dielectric waveguide to hybrid plasmonic waveguide resulting in high transmission with low losses. With this taper maximum transmission, propagation length, mode propagation loss and confinement factor are found as 98%, 274 μm, 0.016 dB/μm and 32%, respectively. Coupler performance has also been investigated with several parametric variations. Apart from that, DtD coupler has been designed and analysed. The obtained results show the efficacy of the proposed coupler for on-chip applications.

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