Polarization rotation and coupling between silicon waveguide and hybrid plasmonic waveguide

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Abstract: We present a polarization rotation and coupling scheme that rotates a TE \(0\) mode in a silicon waveguide and simultaneously couples the rotated mode to a hybrid plasmonic (HP \(0\)) waveguide mode. Such a polarization rotation can be realized with a partially etched asymmetric hybrid plasmonic waveguide consisting of a silicon strip waveguide, a thin oxide spacer, and a metal cap made from copper, gold, silver or aluminum. Two implementations, one with and one without the tapering of the metal cap are presented, and different taper shapes (linear and exponential) are also analyzed. The devices have large 3 dB conversion bandwidths (over 200 nm at near infrared) and short length (< 5 \(\mu m\)), and achieve a maximum coupling factor of \(\sim 78\%\) with a linearly tapered silver metal cap.

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OCIS codes: (230.3120) Integrated optics devices; (250.5403) Plasmonics; (130.5440) Polarization-selective devices.

References and links

1. B. Jalali and S. Fathpour, “Silicon photonics,” J. Lightwave Technol. 24, 4600–4615 (2006).
2. R. Soref, “The past, present, and future of silicon photonics,” IEEE J. Sel. Top. Quantum Electron 12, 1678–1687 (2006).
3. M. Watts and H. Haus, “Integrated mode-evolution-based polarization rotators,” Opt. Lett. 30, 138–140 (2005).
4. H. Deng, D. O. Yevick, C. Brooks, and P. E. Jessop, “Design rules for slanted-angle polarization rotators,” J. Lightwave Technol. 23, 432 (2005).
5. Z. Wang and D. Dai, “Ultrasmall Si-nanowire-based polarization rotator,” J. Opt. Soc. Am. B 25, 747–753 (2008).
6. V. J. Sorger, R. F. Oulton, R.-M. Ma, and X. Zhang, “Toward integrated plasmonic circuits,” MRS bulletin 37, 728–738 (2012).
7. M. L. Brongersma and V. M. Shalaev, “Applied physics the case for plasmonics,” Science 328, 440–441 (2010).
8. N. Engheta, “Circuits with light at nanoscales: optical nanocircuits inspired by metamaterials,” Science 317, 1698–1702 (2007).
9. M. Z. Alam, J. Meier, J. S. Aitchison, and M. Mojahedi, “Supermode propagation in low index medium” in Conference on Lasers and Electro-Optics, OSA Technical Digest (Optical Society of America, 2007), paper JThD112.
10. M. Z. Alam, J. S. Aitchison, and M. Mojahedi, “A marriage of convenience: Hybridization of surface plasmon and dielectric waveguide modes,” Laser Photon. Rev. 8, 394–408 (2014).
11. R. F. Oulton, V. J. Sorger, D. Genov, D. Pile, and X. Zhang, “A hybrid plasmonic waveguide for subwavelength confinement and long-range propagation,” Nature Photon. 2, 496–500 (2008).
12. V. J. Sorger, N. D. Lanzillotti-Kimura, R.-M. Ma, and X. Zhang, “Ultra-compact silicon nanophotonic modulator with broadband response,” Nanophotonics 1, 17–22 (2012).
13. R. F. Oulton, V. J. Sorger, T. Zentgraf, R.-M. Ma, C. Gladden, L. Dai, G. Bartal, and X. Zhang, “Plasmon lasers at deep subwavelength scale,” Nature 461, 629–632 (2009).
14. S. Kim and M. Qi, “Copper nanorod array assisted silicon waveguide polarization beam splitter,” Opt. Express 22, 9508–9516 (2014).
15. R. M. Briggs, J. Grandier, S. P. Burgos, E. Feigenbaum, and H. A. Atwater, “Efficient coupling between dielectric-loaded plasmonic and silicon photonic waveguides,” Nano Lett. 10, 4851–4857 (2010).
16. A. Emboras, R. M. Briggs, A. Najar, S. Nambiar, C. Delacour, P. Grosse, E. Augendre, J. Fedeli, B. de Salvo, H. A. Atwater, and R. Espiau de Lamaestre, “Efficient coupler between silicon photonic and metal-insulator-silicon-metal plasmonic waveguides,” Appl. Phys. Lett. 101, 251117–251117 (2012).
17. Y. Song, J. Wang, Q. Li, M. Yan, and M. Qiu, “Broadband coupler between silicon waveguide and hybrid plasmonic waveguide,” Opt. Express 18, 13173–13179 (2010).
18. L. B. Soldano and E. C. Pennings, “Optical multi-mode interference devices based on self-imaging: principles and applications,” J. Lightwave Technol. 13, 615–627 (1995).
19. S. Kim, Y. Xuan, V. P. Drachev, L. T. Varghese, L. Fan, M. Qi, and K. J. Webb, “Nanoimprinted plasmonic nanocavity arrays,” Opt. Express 21, 15081–15089 (2013).
20. J. Zhang, S. Zhu, S. Chen, G.-Q. Lo, and D.-L. Kwong, “An ultracompact surface plasmon polariton-effect-based polarization rotator,” IEEE Photon. Technol. Lett. 23, 1606–1608 (2011).
21. J. N. Caspers, M. Alam, and M. Mojahedi, “Compact hybrid plasmonic polarization rotator,” Opt. Lett. 37, 4615–4617 (2012).
22. J. N. Caspers, J. S. Aitchison, and M. Mojahidi, “Experimental demonstration of an integrated hybrid plasmonic polarization rotator,” Opt. Lett. 38, 4045–4057 (2013).
23. E. D. Palik, Handbook of Optical Constants of Solids, Vol. 3 (Academic, 1998).
24. A. D. Rakic, A. B. Djurišić, J. M. Elazar, and M. L. Majewski, “Optical properties of metallic films for vertical-cavity optoelectronic devices,” Appl. Opt. 37, 5271–5283 (1998).
25. A. Yariv and P. Yeh, Photonics: Optical Electronics in Modern Communications, 6th ed. (Oxford University, 2006).
26. V. P. Tzolov and M. Fontaine, “A passive polarization converter free of longitudinally-periodic structure,” Opt. Commun. 127, 7–13 (1996).
27. P. R. West, S. Ishii, G. V. Naik, N. K. Emani, V. M. Shalaev, and A. Boltasseva, “Searching for better plasmonic materials,” Laser Photon. Rev. 4, 795–808 (2010).

1. Introduction

Silicon photonics [1–5] and plasmonics [6–8] are two of the most actively investigated research fields that are promising in realizing low-cost and high-density photonic integrated circuits (PICs). The significant benefit of silicon photonics is that it can utilize the well-established CMOS manufacturing technology. However, sizes of most silicon photonic devices are relatively large compared to current electronic devices. Plasmonics has attracted extensive research interest due to its ability to confine the light tightly, bringing down the plasmonic device size to subwavelength scale. However, the main drawback of plasmonics is the high absorption loss from metals. To mitigate the challenges of large device footprint and high loss, a promising approach is to integrate silicon photonics and plasmonics into a hybrid system [9–11]. To that end, an efficient coupler between dielectric waveguides and plasmonic devices is an essential component.

A typical plasmonic waveguide consists of a metallic waveguide and one or more layers of dielectric loading, which can be either patterned or blanket. Recently, several designs of Si to plasmonic waveguide couplers have been reported [15–17]. A Si waveguide to dielectric-loaded plasmonic waveguide coupler was demonstrated with a high coupling efficiency (\( \sim 80\% \)) [15]. Also, an efficient coupler between Si and metal-insulator-silicon-metal waveguides was demonstrated with a coupling loss of 2.5 dB [16]. A broadband coupler between Si and hybrid plasmonic (HP) waveguides with a tapered structure was suggested with a maximum coupling efficiency of \( \sim 70\% \) [17]. This work has practical importance because the HP waveguide is a relatively efficient plasmonic waveguide with its long propagation length and high field confinement [9–11]; the HP configuration has also been used as an ultracompact electro-optical modulator [12] and a nano-laser [13] with a great potential for future PICs. However, in [17], the coupler was designed for TM mode (electric field perpendicular to the surface) to HP mode only. In silicon photonics in general, TE modes (electric field parallel to the surface) are more desirable and widely used due to their higher coupling efficiency and ease of fabrication. Thus, to utilize the Si waveguide to HP waveguide coupler scheme in [17], an additional polarization
Fig. 1. Schematic of the polarization rotation and coupling (PRC) structure. The inset shows the cross-sectional view and parameters; \( h_{\text{Si}} \), \( h_{\text{SiO}_2} \), and \( h_{\text{Cu}} \) are the heights of Si, SiO\(_2\), and Cu, respectively. \( w_1 \) is the width of both Si and HP waveguides, and \( w_2 \) is the width of Cu and SiO\(_2\) in the PRC region. Si, SiO\(_2\), Cu, and PMMA regions are colored in blue, grey, yellow, and cyan respectively. The PMMA cladding is not shown in the 3D illustration.

rotator is required, which decreases coupling efficiency and increases the device size.

For the rotation of polarization, exciting a hybrid eigenmode with an angled optical axis is necessary, and the waveguide structure essentially requires an asymmetric cross-section. Various types of asymmetric waveguide structures have been proposed and demonstrated as a polarization rotator (PR), such as a twisted waveguide [3], a slanted sidewall waveguide [4], and a corner cut waveguide [5]. There are, in general, two types of PR schemes, based on mode-evolution [3] or mode-coupling [4, 5]. The mode-coupling based PRs use the multimode interference [4, 5, 18] of two hybrid modes in a PR, and usually have shorter conversion length compared to the mode-evolution based PRs. However, the performance is sensitive to the phases of coupled modes, making the device wavelength-sensitive and difficult to fabricate. On the other hand, the mode-evolution based PRs are more tolerant to the fabrication errors and inherently broadband [3]. Plasmonic metal nanostructure can confine light down to the subwavelength scale [19], and may reduce the device size and enhance the operating bandwidth [14]. For the PR applications, an asymmetric waveguide cross-section can be introduced by covering the top or side-wall surfaces of silicon waveguide, with a metal, asymmetrically [20–22]. In these cases, hybrid modes with a plasmonic structure introduce a large effective refractive index differences, resulting an ultrashort conversion length.

In this paper, we present ultrashort polarization rotation and coupling (PRC) structures that rotate the TE\(_0\) mode in a Si waveguide (TE\(_{0,\text{Si}}\)) and couple it to the HP\(_0\) mode in a HP waveguide. We use an asymmetric hybrid plasmonic waveguide structure for the rotation of polarization and coupling; the metal and low-index material cap area is etched partially. Two PRC schemes are presented without (Fig. 1) and with (Fig. 8) metal tapers. The effects of different metal caps (copper, silver, gold, and aluminum) and taper shapes (linear and exponential) are evaluated, and spectral responses are also presented.
Fig. 2. From left to right, normalized mode profiles showing the $|E|$, at Si waveguide, PRC, and HP waveguide cross-sections. Geometric parameters are set to $h_{\text{Si}}=230$ nm, $h_{\text{SiO}_2}=50$ nm, $h_{\text{Cu}}=100$ nm, $w_1=380$ nm, and $w_2=200$ nm.

2. Polarization rotation and coupling (PRC)

2.1. Design of the PRC

Figure 1 shows the schematic of the PRC structure. A Si waveguide and a HP waveguide are connected with the PRC structure, where the TE$_0$ mode is converted to the HP$_0$ mode. The inset shows the cross-sectional view and parameters; $h_{\text{Si}}$, $h_{\text{SiO}_2}$, and $h_{\text{Cu}}$ are the heights of Si, SiO$_2$, and Cu, respectively. $w_1$ is the width of both Si and HP waveguides, and $w_2$ is the width of Cu and SiO$_2$ on PRC region. We first choose Cu as the plasmonic material for its compatibility with CMOS processing, and cover it with PMMA to avoid its oxidation. Waveguide heights are fixed at $h_{\text{Si}}=230$ nm, $h_{\text{SiO}_2}=50$ nm, and $h_{\text{Cu}}=100$ nm, and width $w_1$ is chosen to be 380 nm so that the phase of TE$_{0,\text{Si}}$ mode is matched with the phase of HP$_0$ mode.

Figure 2 shows the normalized mode profiles ($|E|$) at Si waveguide, PRC ($w_2=200$ nm), and HP waveguide regions from left to right. The free space wavelength is $\lambda_0=1550$ nm throughout the paper. Notice that the effective refractive index ($n_{\text{eff}}$) of TE$_{0,\text{Si}}$ mode and the $n_{\text{eff}}$ of HP$_0$ mode are identical ($n_{\text{eff}}=2.19$) so as to match the phase of both modes. Hybrid modes (PRC$_0$ and PRC$_1$) are excited in the PRC region, due to the asymmetry of the structure with $w_2$. These two lowest hybrid modes have a large overlap in field components, and experience interference with each other through the conversion length of $L_c$. The conversion length of this multimode interference can be estimated by $L_c = \pi / (\beta_0 - \beta_1)$ [18], where $\beta_0$ and $\beta_1$ are the propagation constants of PRC$_0$ and PRC$_1$ modes, respectively, which are given by $\beta_i = n_{\text{PRC}_i} k_0$. Figure 3 shows the calculated $n_{\text{eff}}$ for PRC$_0$ (red circle line) and PRC$_1$ (black square line) modes, and corresponding $L_c$ (blue line) as a function of $w_2$. Notice that the conversion length is very short (between 3 $\mu$m and 6 $\mu$m), compared to that of other conventional polarization rotators (typically, tens or hundreds of micrometers). Previously, an asymmetric Si nanowires were used to rotate the polarization with a conversion length of $\sim 22.1\mu$m [5]. Here, a shorter polarization conversion lengths are achieved ($\sim 4.5\mu$m) by using the asymmetric HP waveguide, simultaneously coupling to the HP$_0$ mode. The short conversion length is due to the large $n_{\text{eff}}$ difference between the two lowest order modes (PRC$_0$ and PRC$_1$). However, there is a trade-off between conversion length and coupling factor. The green line indicates the position of $n_{\text{eff}} = 2.19$, which corresponds to the $n_{\text{eff}}$ of TE$_{0,\text{Si}}$ and HP$_0$ modes. The coupling factors, at the interfaces
between PRC and Si or HP waveguide, will be reduced as the \( n_{\text{eff}} \) of PRC0 and PRC1 modes deviate from this green line, because of the phase mismatch at the interfaces. On the other hand, the more deviations from this green line result in the shorter conversion length because of the larger \( n_{\text{eff}} \) difference between PRC0 and PRC1 modes.

### 2.2. Numerical method

To evaluate the performance of the designed PRC, 3D finite element method (FEM) simulations are conducted using the COMSOL Multiphysics®. The refractive indices of Si, SiO\(_2\), and PMMA are chosen to be \( n_{\text{Si}}=3.445 \), \( n_{\text{SiO}_2}=1.445 \), and \( n_{\text{PMMA}}=1.481 \) assuming them to be lossless, and the complex refractive index of Cu is used considering both material dispersion and loss [23, 24]. The TE\(_0\) mode is excited at port 1, and the coupling factor to the HP\(_0\) mode (\( CF_{\text{HP}_0} \)) is evaluated by the power transmission to the HP\(_0\) mode at port 2, i.e.,

\[
CF_{\text{HP}_0} = \frac{P_{\text{HP}_0,2}}{P_{\text{TE}_0,1}},
\]

where \( P_{\text{TE}_0,1} \) is the input power of the TE\(_0\) mode at port 1, and \( P_{\text{HP}_0,2} \) is the output power of the HP\(_0\) mode at port 2. The output power of the TE\(_0\) mode at port 2 is also calculated to evaluate the polarization conversion efficiency (PCE), which is defined as 

\[
PCE = P_{\text{TE}_0,2}/(P_{\text{HP}_0,2} + P_{\text{TE}_0,2}).
\]

Boundary mode analysis is conducted to excite the TE\(_0\) mode at port 1 and to decompose the HP\(_0\) and TE\(_0\) modes at port 2. The output power of the HP\(_0\) mode is evaluated by the field decomposition as the following [25]:

\[
P_{\text{HP}_0,2} = \frac{1}{2} \text{Re} \left[ \frac{\int (\mathbf{E}_{\text{FEM}} \times \mathbf{H}_{\text{HP}_0}) \cdot ds}{\int (\mathbf{E}_{\text{HP}_0} \times \mathbf{H}_{\text{HP}_0}) \cdot ds} \right],
\]

where \( \mathbf{E}_{\text{FEM}} \) and \( \mathbf{H}_{\text{FEM}} \) are, respectively, the electric and magnetic fields components of the 3D FEM simulations, and \( \mathbf{E}_{\text{HP}_0} \) and \( \mathbf{H}_{\text{HP}_0} \) are, respectively, the electric and magnetic fields components of the HP\(_0\) mode calculations for the same geometric dimensions. The surface integrations of the output power in propagation direction (z-direction) are conducted over the waveguide cross-sections. The process for evaluating \( P_{\text{TE}_0,2} \) is similar, but \( \mathbf{E}_{\text{HP}_0} \) and \( \mathbf{H}_{\text{HP}_0} \) are replaced by \( \mathbf{E}_{\text{TE}_0,2} \) and \( \mathbf{H}_{\text{TE}_0,2} \), respectively.
Fig. 4. Normalized field plots of real $E_x$ (above) and $E_y$ (below) components at the middle of waveguide width $w_1$ ($yz$-plane), when $w_2=180$ nm, $L_c=4$ $\mu$m, and $\lambda_0=1550$ nm.

2.3. Results and discussion

Figure 4 shows the normalized field plots at the middle of waveguide width $w_1$ ($yz$-plane), when $w_2=180$ nm, $L_c=4$ $\mu$m, and $\lambda_0=1550$ nm. Above is the real $E_x$ and below is the real $E_y$. Notice that, in the Re($E_x$) plot (above), the excited TE$_0$ mode at the port 1 (left side of the figure) gradually disappears as wave propagates (in $z$-direction) through the PRC region. On the other hand, in the Re($E_y$) plot (below), the HP$_0$ mode begins to appear as the TE$_0$ mode disappears, and couples to the port 2 (right side of the figure). Here, the TE$_0$ mode is rotated and coupled to the HP$_0$ mode through the conversion length $L_c$ of the PRC structure.

Figures 5(a) and 5(b) show the calculated CF$_{HP0}$ and PCE, respectively, as a function of $L_c$ for different waveguide width $w_2$: $w_2 = 160$ nm (blue), $w_2 = 180$ nm (green), $w_2 = 200$ nm (red), $w_2 = 220$ nm (cyan), $w_2 = 240$ nm (purple), and tapered PRC (dashed black). Notice that the maximum CF$_{HP0}$ is over 60% with an ultrashort conversion length $L_c$ of $\sim 4$ $\mu$m. Also, the maximum PCE is $\sim 100\%$ with $w_2 = 180$ nm and $w_2 = 200$ nm. The ripples on the graph are due to the Fabry-Pérot type resonances from the reflected lights within the PRC region. As $w_2$ increases, the conversion lengths $L_c$ of the maximum CF$_{HP0}$ and PCE increase; this is consistent with our previous finding.
on conversion length in Fig. 3. The degree of $CF_{HP_0}$ is affected by the coupling efficiencies between other waveguides and the $PCE$, which depend on the $w_2$ significantly. There are two loss factors that determine the coupling efficiencies. One is the reflection or scattering loss that comes from the modes mismatch between two different waveguide schemes, and the other is the material loss from the metal. As we increase the $w_2$, the reflection or scattering loss will be reduced because the phases of PRC$_i$ modes approach to the phases of TE$_{0, Si}$ and HP$_0$ modes as shown in Fig. 3. Also, increasing the $w_2$ will enhance the mode overlap between PRC$_i$ and HP$_0$ modes, improving the $CF_{HP_0}$. However, the material loss will be increased due to more exposure to the metal. The $PCE$s also vary for different $w_2$, because $w_2$ determines the field distribution of PRC$_0$ and PRC$_1$ modes, and essentially the modes overlap between them. The $PCE$ of polarization rotator, which is based on hybrid modes interference, depends on the rotational angle of the optical axis $\theta$ and conversion length $L_c$ as the following [4]:

$$PCE = \sin^2(2\theta) \sin^2\left(\frac{\pi L}{2L_c}\right),$$

(2)

where, $L$ is the actual length of the structure. The rotational angle of optical axis $\theta$ can be defined by the distributions of the transverse magnetic field components as follows [4, 26]:

$$R = \tan(\theta) = \frac{\int |H_x(x, y)|^2 \, ds}{\int |H_y(x, y)|^2 \, ds}.$$

(3)

FEM mode calculations are conducted to find the field distributions for different $w_2$, then $\theta$ is obtained using the Eq. (3). Figure 6 shows the estimated $PCE$ of using the Eq. (2) for different $w_2$. Here, we assume the device length $L = L_c$; the $PCE$ depends solely on the optical axis rotation angle $\theta$, which is determined by the field distributions of the hybrid mode PRC$_1$. Notice that, in Fig. 6, the maximum $PCE$ occurs around $w_2 = 180$ nm, and the $PCE$ decreases as $w_2$ increases. This is consistent with the rigorous 3D FEM simulation results in Fig. 5(b), where the degree of $PCE$ has the maximum value when $w_2$ is between 180 nm and 200 nm, and then decrease as $w_2$ increases. As a result of these related effects of coupling efficiencies and $PCE$, the maximum $CF_{HP_0}$ increases from $w_2 = 160$ nm to $w_2 = 200$ nm because of the reduced reflection or scattering loss, then starts to decrease after that because of the reduced $PCE$ and increased material loss.
3. Tapered polarization rotation and coupling (TPRC)

3.1. Design of the TPRC

To reduce the reflection or scattering loss at the interfaces, a metal taper can be introduced into the PRC structure. Figure 7 shows the schematic of the tapered polarization rotation and coupling (TPRC) structure. The geometric parameters and material components are set to the same as the PRC in Fig. 1. The $C_{F_{HP_0}}$ and $PCE$ as a function of $L_c$ for the TPRC are plotted in Fig. 5(a) and 5(b), respectively, with dashed black lines. Notice that the $C_{F_{HP_0}}$ of TPRC (the maximum $C_{F_{HP_0}} \sim 64\%$) is higher than the previous PRC designs, and the $PCE$ of TPRC is comparable (the maximum $PCE \sim 100\%$) with other PRC designs. Furthermore, the TPRC has a broader fabrication tolerance in $L_c$. In tapers, an abrupt phase difference at the interface between TPRC and HP waveguide is avoided, thus improving the coupling efficiency at this interface. However, there will still be an abrupt phase difference at the interface between Si waveguide and TPRC, where a sharp metal tip exists. Typically, in all-dielectric waveguide, a gradual taper that keeps an asymmetric waveguide cross-section gives an adiabatic polarization rotation [3], as the underlying principle of polarization rotation is mode-evolution, and the transmission power of the rotated mode increases as the device length increases (no sinusoidal trend as in Fig. 5). However, the TPRC design that we present here is not based solely on mode-evolution, rather it is a combination of mode-coupling and mode-evolution. The critical difference from the purely dielectric taper is that highly confined plasmonic modes are excited at the narrow metal tip. This gives an abrupt phase difference and as a result, two different modes can be excited and converted into either PRG_0 or PRG_1. This would cause mode-coupling based interference and hence the sinusoidal trend. There is, still, an adiabatic mode-evolution between TPRC and HP waveguide (from PRG_0 to HP_0 mode); and this gives a higher fabrication tolerance in $L_c$ compared to PRC as shown in Fig. 5. The $L_c$ for the peak coupling factors ($\sim 4.5 \mu m$) is a little bit longer than PRC designs, but it is still very short compared to other dielectric polarization rotators.
3.2. Different metal caps

Up to now, we have employed Cu as the plasmonic material due to its low resistivity and widespread use in current CMOS manufacturing technology. However, the material loss can be reduced by replacing the Cu with other plasmonic materials such as silver, gold, and aluminum [23, 24, 27]. To compare the performance of other plasmonic metals, more simulations are conducted on the same TPRC structure, but with different port widths of \( w_2 = 380 \text{ nm} \) (Cu), 375 nm (Ag), 380 nm (Ag), and 355 nm (Al), which corresponds to the optimized value for each material. Figure 8 shows the calculated \( CF_{HP0} \) as a function of \( L_c \), which is similar to Fig. 5(a), but for the TPRC with different metal caps: Cu (blue), Ag (green), Au (red), and Al (cyan). Notice that, in Fig. 8, the TPRC with Ag, Au, or Al metal cap has higher \( CF_{HP0} (> 70\%) \) than that with Cu metal cap. Ag and Au are well known as good plasmonic materials, with less absorption losses compared to other materials [27]. Here, the maximum \( CF_{HP0} \) of about 78% is achieved with Ag metal cap, and about 71% with Au. For Al, even though Al has higher material loss (larger imaginary permittivity) compared to other metals, it is highly metallic with a large negative permittivity (\( \varepsilon_{Al} = -229.78 + i46.12 \) at \( \lambda_0 = 1550 \text{ nm} \) [24]). Thus, the skin depth of Al is very low and less percentage of the total optical power is propagating in Al. This reduces the overall material absorption loss and yields lower propagation loss for the HP mode with Al cap than those with Au or Cu metal caps [27]. As a result, TPRC with Al shows higher \( CF_{HP0} \) than TPRC with Au or Cu, achieving the maximum \( CF_{HP0} \) of about 73%.

3.3. Different taper shapes

The effect of taper shapes is also evaluated with a linear [Eq. (4)] and exponential [Eq. (5)] taper shapes which can be described as the following:

Linear taper:

\[
L_c' = \frac{z - z_0}{z_1 - z_0} f(z') = z'
\]  

(4)

Exponential taper:

\[
L_c' = \frac{z - z_0}{z_1 - z_0} f(z', a) = \frac{e^{az'} - 1}{ea^a - 1}
\]  

(5)

where \( z_0 \) and \( z_1 \) are the starting and ending points in \( z \) direction, and \( a \) determines the degree of growth rate in exponential taper function. Figure 9(a) shows the contour of tapers in \( xy \)-plane with different taper shapes: linear (blue) and exponential tapers with \( a = 1 \) (green) and \( a = -1 \).
Fig. 9. (a) Taper shapes according to shape function in Eq. (4) and Eq. (5), and (b) Corresponding $CF_{HP0}$ as a function of $L_c$ for different taper shapes: linear (blue), and exponentials with $a = 1$ (green) and $a = -1$ (red).

Fig. 10. The $CF_{HP0}$ as a function of the free space wavelength $\lambda_0$ for the PRC ($w_2 = 180 \mu m$ and $L_c = 4 \mu m$, in blue) and the TPRC ($L_c = 5 \mu m$, in green).

(red). Here, $z_0$ and $z_1$ are set to 0 and $L_c$, respectively, and the width $w_1$ is multiplied to each taper function. Cu is used as the metal cap. Figure 9(b) is the calculated $CF_{HP0}$ as a function of $L_c$, which corresponds to each taper shape in Fig. 9(a). Calculations show that the exponential taper with $a = 1$ has higher $CF_{HP0}$ than liner taper and exponential taper with $a = -1$; this is because, for the exponential taper with $a = 1$, more gradual tapering (slowly increasing $w_2$) is introduced at narrow edge region where the mode changes abruptly. With the exponential taper ($a = 1$), about 5% increase in $CF_{HP0}$ has been achieved.

4. Bandwidths of PRC and TPRC

The bandwidths of PRC and TPRC are also evaluated, and Fig. 10 shows the calculated $CF_{HP0}$ as a function of the free space wavelength $\lambda_0$, ranging from 1400 nm to 1700 nm, for PRC (blue line) and TPRC (green line). Cu is used as the metal cap for every case, and the geometric dimensions are chosen to have the maximum $CF_{HP0}$ for each case: the PRC with $w_2 = 180 \mu m$ and $L_c = 4 \mu m$ and the TPRC with $L_c = 5 \mu m$ and linear taper. Other parameters are set to the same as in the original designs for each case. Notice that the TPRC has broader bandwidth than...
PRC. In general, the mode-evolution based PR has broader bandwidth than the mode-coupling based PR [3], and this is consistent with our results as TPRC is based on a combination of mode-evolution and mode-coupling, while PRC is solely based on mode-coupling. Nevertheless, even the mode-coupling based PRC has a relatively large bandwidth compared to a typical all-dielectric mode-coupling based PR; this is because the plasmonic modes (HP0, PRC0, and PRC1 modes) are relatively less sensitive to the wavelength compared to other all-dielectric waveguide modes. If we define an operating 3-dB bandwidth as $CF_{HP0} \geq 50\%$ (coupling loss is below 3 dB), the operating bandwidths are $\sim 200$ nm and $\sim 250$ nm for PRC and TPRC, respectively.

5. Conclusion

In conclusion, we presented a class of polarization rotation and coupling designs that rotate the TE0 mode and simultaneously couple it to the HP0 mode. With a Cu metal cap, which is compatible with current CMOS technology, the coupling factor to the HP0 mode can be over 60% and the PCE is almost 100%. About 2% or 5% higher coupling factors can be achieved with a linear or exponential metal taper, respectively. The device sizes are very short with a conversion length of about 4.5 $\mu$m, and the 3 dB bandwidths are over 200 nm. Higher performance can be achieved with different metal caps, and about 78% of coupling factor is achieved with a Ag metal cap. The polarization rotation and coupling scheme that we presented here has potential in future Si/plasmonic hybrid PICs.

Acknowledgments

This work is supported in part by National Science Foundation grant CMMI-1120577, Defense Threat Reduction Agency grants HDTRA110-1-0106 and HDTRA1-07-C-0042, National Institute of Health grant 1R01RR026273-01, Air Force Office of Scientific Research grant FA9550-12-1-0236, and DARPA PULSE program grant W31P40-13-1-0018 from AMRDEC.