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Corrigendum: Vertical polarization beam splitter using a hybrid long-range surface plasmon polariton waveguide (2014 *J. Opt.* 16 025501)

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We miscalculated the extinction ratio of the bar-port as a function of wavelength in the published version of our paper [1]. The corrected version of figure 5(b) is shown below. The corrected sentences read as follows: 'The 20 dB bandwidth is more than 40 nm, which covers the C-band. The insertion losses of the TE- and TM-polarization modes on the entire C-band are less than 0.035 dB and 0.2 dB, respectively.'

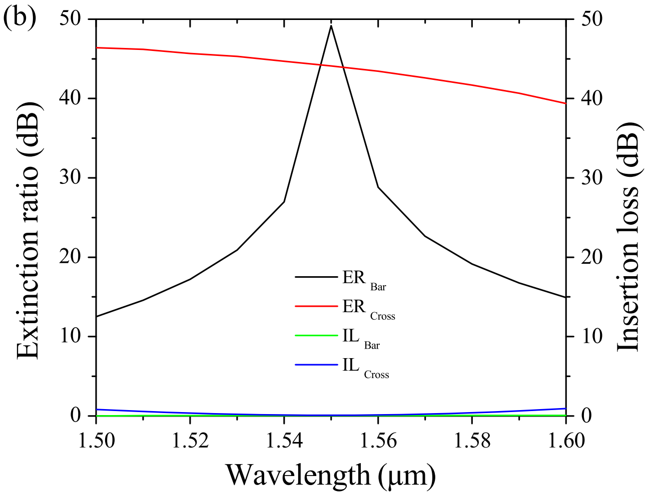

Figure 5(b).

Reference [19] is revised as 'Johnson P B and Christy R W 1972 Optical constants of the noble metals *Phys. Rev.* B **6** 4370–79'.

Reference

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Abstract

A vertical polarization beam splitter using a hybrid long-range surface plasmon polariton (LR-SPP) waveguide is proposed for three-dimensional integration of silicon photonic circuits in a chip. The device is based on a three-port directional coupler that is operated based on mode coupling theory. The hybrid LR-SPP waveguide as the central waveguide in a three-port directional coupler plays a key role in transferring the transverse-magnetic (TM)-polarization mode from the input port to the cross port, which is configured with horizontal and vertical offsets. A 9.7 μm-long vertical polarization splitter with an extinction ratio of 30 dB in the C-band is achieved. The effects of dimensional tolerances are also investigated. The vertical polarization splitter is highly compatible with a complementary metal–oxide–semiconductor (CMOS) fabrication process based on the silicon-on-insulator (SOI) platform.

Keywords: polarization-selective devices, integrated optics devices, guided waves
PACS numbers: 42.82.-m, 78.66.Bz

(Some figures may appear in colour only in the online journal)

1. Introduction

Plasmonics based on surface plasmon polaritons (SPPs) has been attracting a great deal of attention because of its ability to manipulate light on subwavelength scale dimensions that break the diffraction limit [1]. In combination with silicon photonics, plasmonics has extended its applications in photonic integrated circuits (PICs). A variety of Si-based hybrid plasmonic components have been developed to date, including waveguides, dividers, couplers, resonators, modulators and detectors [2–9]. Si-based plasmonic waveguide devices are paving a promising way to realize system-level plasmonic integrated circuits both on-chip and intra-chip [10, 11].

As an important basic component, polarization beam splitters have been attracting much attention. Such devices allow us to develop polarization-independent PIC systems and to double the data processing capability by using the TE- and TM-polarization modes simultaneously. Compared to Si-based polarization beam splitters [12, 13], plasmonic-based devices provide a compact device design and a satisfactorily high extinction ratio [14, 15]. This is attributed to the highly birefringent nature of the plasmonic waveguide, where a TM-polarized electromagnetic surface wave is allowed at the metal–dielectric interface. Directional coupler-type polarization beam splitters have demonstrated excellent performance in splitting and combining polarized light signals in conventional two-dimensional (2D) PICs. However, there is still a demand to develop innovative polarization beam splitters to support the achievement of three-dimensional (3D) multilayer PICs in a chip.

In this paper, we propose a vertical polarization beam splitter using a hybrid long-range surface plasmon polariton (LR-SPP) waveguide to satisfy this requirement. The optical device is based on the polarization-dependent nature of the central waveguide in a three-port directional coupler. The optical characteristics are investigated using the finite element method and eigenmode expansion calculation at a wavelength

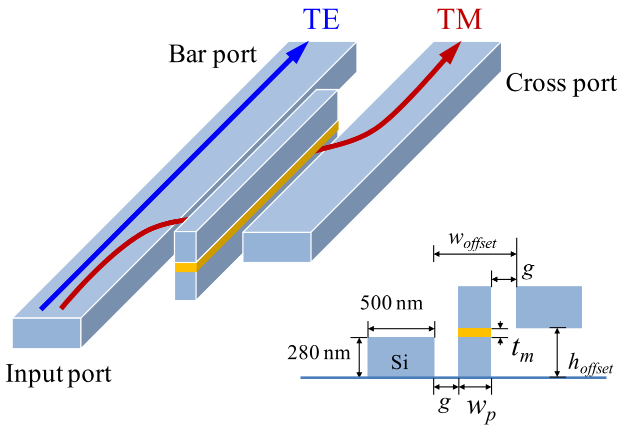

Figure 1. Schematic views of a vertical polarization beam splitter using a low-loss hybrid long-range surface plasmon polariton (LR-SPP) waveguide for three-dimensional integration of silicon photonic circuits in a chip.

of 1.55 μm. Numerical simulation shows that the hybrid LR-SPP waveguide plays a key role in transferring the TM-mode light. The effects of the dimensional tolerances of the waveguide on the polarization splitter performance are also investigated.

2. Architectural concept and characterization

The architectural concept of the proposed vertical polarization beam splitter is shown in figure 1. It consists of a single hybrid LR-SPP waveguide and two Si waveguides. A 280-nm thick 500-nm wide Si waveguide for the input port (and hence the bar port) is formed on the standard silicon-on-insulator (SOI) platform. A Si–metal–Si hybrid LR-SPP waveguide with width w_p is placed parallel to the input Si waveguide. The height of the hybrid LR-SPP waveguide is 560 nm + t_m, where t_m is the metal thickness. The second Si waveguide for the cross port is finally placed next to the hybrid LR-SPP waveguide with vertical and horizontal offsets. Since the three waveguides are separated by a gap of 200 nm (g), the horizontal offset (w_{offset}) and vertical offset (h_{offset}) are $w_{offset} = 400\ \text{nm} + w_p$ and $h_{offset} = 280\ \text{nm} + t_m$, respectively. Cu has been widely used recently as a cladding for plasmonic waveguides so that we applied Cu in the hybrid plasmonic waveguide [9].

The operation of the vertical polarization beam splitter is based on mode coupling theory. Similar to conventional LR-SPP waveguides [16–18], the hybrid LR-SPP waveguide supports mainly the transverse magnetic (TM)-mode so that the TM-mode is directionally coupled to the cross port, whereas the transverse electric (TE)-mode continues its propagation along the bar port with a satisfactory extinction ratio. In addition, efficient three-dimensional (3D) beam splitting is also possible because the field distribution of the tall central hybrid LR-SPP with high aspect ratio extends above the cross port Si waveguide.

The effective refractive indices of the hybrid LR-SPP waveguide ($N_{eff,LRSPP}$) at a wavelength of 1.55 μm are calculated by the finite element method, using the commercial software FIMMWAVE. For the hybrid LR-SPP waveguide, the Cu thickness t_m is 10 nm and the height is 570 nm. The refractive indices of the Si and SiO_2 are 3.476 and 1.444, respectively. The complex refractive index of Cu is dependent on the wavelength [19].

The dependence of $N_{eff,LRSPP}$ for the hybrid LR-SPP waveguide on the waveguide width w_p is shown in figure 2(a), including $N_{eff,Si}$ of a 500-nm wide 280-nm thick Si waveguide. The inset displays the field distribution of the hybrid LR-SPP stripe mode that is supported by the plasmonic waveguide. Similar to previous works [20, 21], the guided mode is like a combination of the LR-SPP mode and the waveguide mode of the Si waveguide. Thus, $N_{eff,LRSPP}$ of the plasmonic waveguide is complex, $N_{eff,LRSPP} = \text{Re}[N_p] - \text{Im}[N_p]$. We considered its real part Re[N_p] to determine the optimized waveguide width that provides the maximum power transfer of the TM-polarization mode from the input port to the cross port. Re[N_p] of the TM-polarization mode in the hybrid plasmonic waveguide is higher than that of TE-polarization mode. $N_{eff,Si}$ of the TE- and TM-polarization mode in the 500-nm wide 280-nm thick Si waveguide are 2.626 and 2.210, respectively.

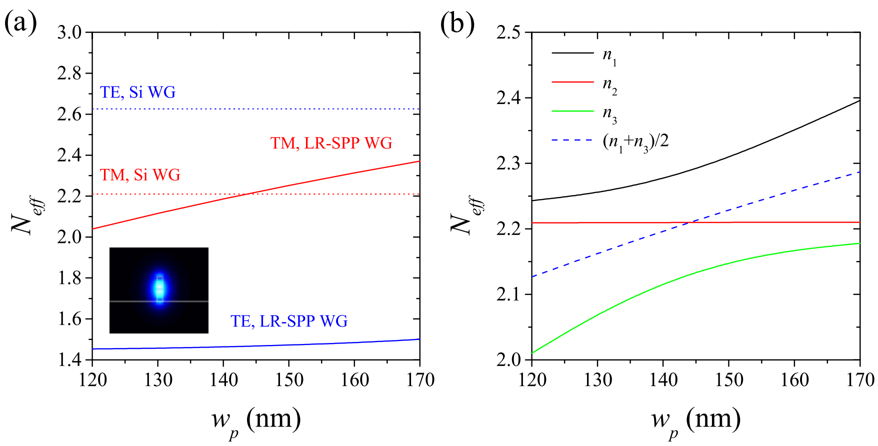

Figure 2. (a) Effective refractive indices of the hybrid LR-SPP waveguide. For the TM-polarization mode, the indices are matched at $g \approx 142$ nm. (b) TM-polarization super-modes in the coupler section as a function of waveguide width w_p. The super-modes (TM_1, TM_2, and TM_3) have effective refractive indices n_1, n_2, and n_3, respectively.

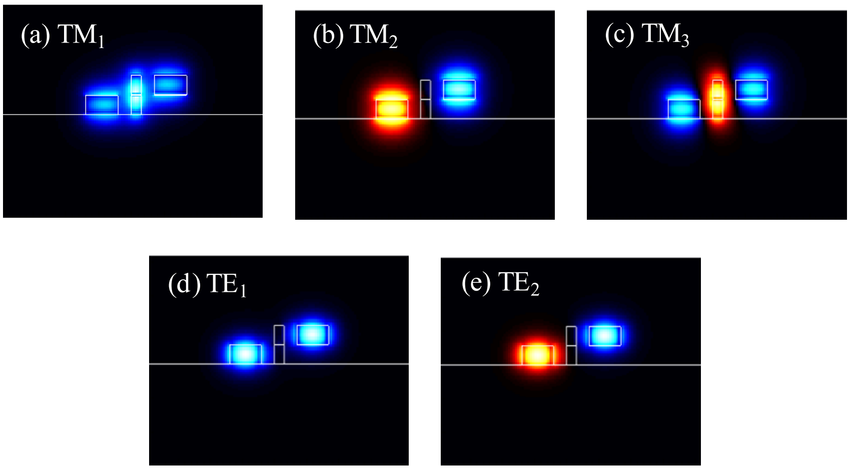

Figure 3. Calculated field distributions of all the super-modes in the coupler section. (a) and (c) Symmetric TM-polarization super-modes, (b) antisymmetric TM-polarization super-mode. (d) and (e) Symmetric and antisymmetric TE-polarization super-modes.

When the waveguide width of the hybrid plasmonic waveguide is 142 nm, Re[N_p] of the TM-polarization mode is the same as that of the Si waveguide.

The optimized coupling length (L_c) that provides efficient maximum optical power transfer can be found by calculating N_{eff} of the TM-polarization super-modes for the coupler section. Figures 3(a)–(c) show the calculated field distributions of all the super-modes: two symmetric super-modes and one antisymmetric super-mode. We denoted N_{eff} of the super-modes (TM$_1$, TM$_2$, and TM$_3$) as n_1, n_2, and n_3, respectively, where n_2 represents the antisymmetric one. To transfer maximum optical power, the effective indices of the super-modes satisfy the following equation [22, 23],

$$2n_2 - n_1 - n_3 = 0. \quad (1)$$

With this condition, the coupling length (L_c) can be calculated easily as

$$L_c = \pi/(\beta_1 - \beta_3) = \lambda/2(n_1 - n_3). \quad (2)$$

As shown in figure 2(b), the effective indices of the three TM-polarization super-modes in the coupler section satisfy equation (1) when $w_p = 144$ nm. Based on equation (2), we obtained that $L_c = 9.75$ μm. For the TE-polarization, the effective indices of the even and odd super-modes are 2.6272 and 2.6269, respectively, and hence, $L_c = 2.58$ mm. Therefore, the TM-polarization mode is coupled efficiently to the cross port with this short coupling length of about 10 μm.

By using FIMMPROP, which is linked with FIMMWAVE, we evaluated the performance of the proposed plasmonics-based vertical polarization beam splitter. The calculation is based on eigenmode expansion, bidirectional mode propagation, and mode matching. We launched the TM- and TE-polarization modes at the input and evaluated the output optical power of the bar and cross port waveguides. Figure 4 shows the guided mode propagation in the proposed vertical polarization beam splitter for the TE- and TM-polarization modes, respectively. With the optimized coupling length of 9.75 μm, the TM-polarization mode is coupled into the hybrid LR-SPP waveguide and, consequently, most power is transferred to the cross port, which is configured with horizontal and vertical offsets (see figure 4(b)). On the other hand, the TE-polarization mode passes through the bar port without the slightest mode coupling. This is clearly shown in figure 4(a). As a result, we can use the two polarization modes simultaneously in a chip.

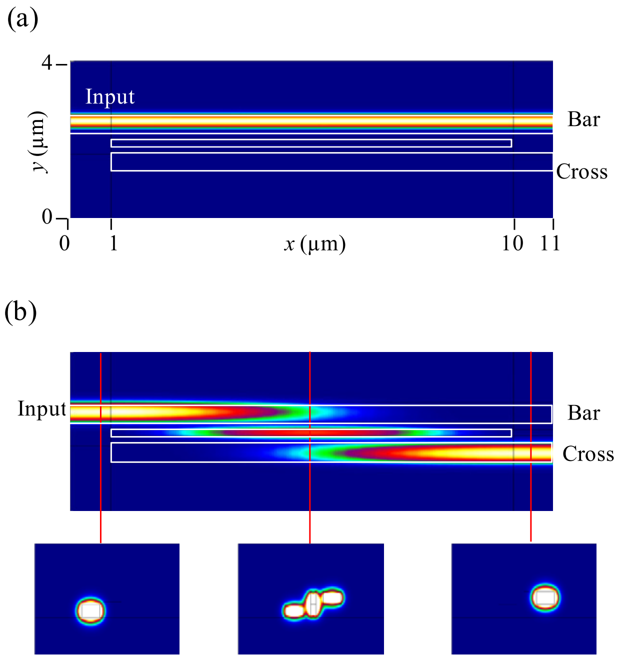

Figure 4. Propagation of the guided modes in the vertical polarization beam splitter for (a) TE- and (b) TM-polarization mode excitations.

Figure 5(a) shows the dependence of optical power transfer on the coupling length. At a coupler length of 9.75 μm, we can obtain 99.7% power transfer of the TM-polarization mode from one Si waveguide to the other. The propagation loss of the hybrid LR-SPP waveguide is comparatively low because the field intensity of the guided mode is confined mostly in the dielectric layers rather than the metal [19]. The plasmonic waveguide has a propagation loss of 0.027 dB μm^{-1}.

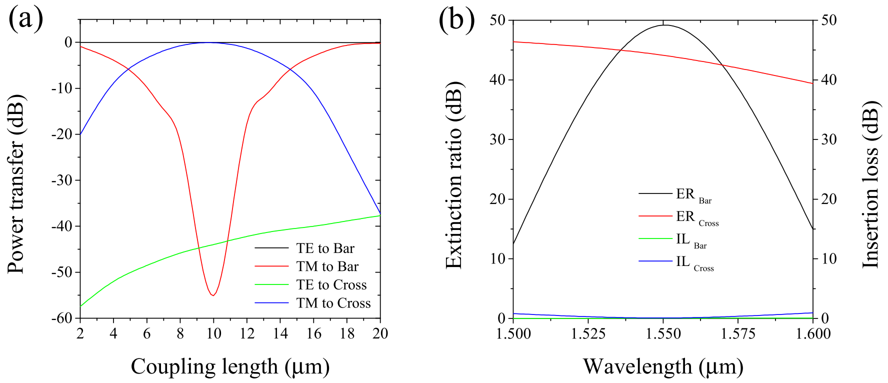

Figure 5. (a) Dependence of power transfer on the coupling length. (b) Extinction ratios and insertion losses of each port for a 9.75 μm-long coupler as a function of wavelength.

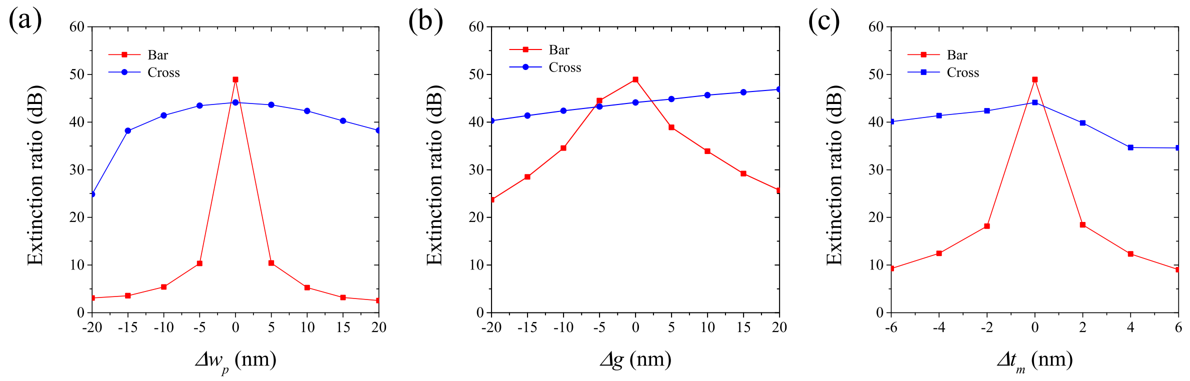

Figure 6. Dependence of the extinction ratios of each port on (a) Δw_{p}, (b) Δg, and (c) Δt_{m}.

However, this value is negligible because of the very short coupling length of 9.75 μm. For the TE-polarization mode, the optical power transferred to the cross port is very low because the coupler length is too short for the mode. Even coupled, most optical power of the mode is attenuated in the plasmonic waveguide because of the high propagation loss of 0.18 dB μm^{-1}. Figure 5(b) shows the extinction ratios and insertion losses of each port for a 9.75 μm-long coupler as a function of wavelength. The 30 dB bandwidth is about 60 nm, which covers the C-band. The insertion losses of the TE- and TM-polarization modes on the entire C-band are less than 0.5 dB and 0.05 dB, respectively.

The dependence of the extinction ratios of each port on dimensional variations (namely, the change in w_{offset} and h_{offset}) are exhibited in figure 6 as a function of Δw_{p}, Δg, and Δt_{m}. For the cross port, the extinction ratios are almost independent of the dimensional changes because the hybrid LR-SPP waveguide couples the TM-polarization mode strongly regardless of dimensional changes. On the other hand, the extinction ratio of the bar port shows a dramatic dependence of behavior on Δw_{p}, Δg, and Δt_{m}. We found that the proposed polarization beam splitter can maintain a 10 dB extinction ratio for a width variation of the center plasmonic waveguide of $\pm$5 nm, a 35 dB extinction ratio for a gap width variation of $\pm$10 nm, and a 12 dB extinction ratio for a metal strip thickness variation of $\pm$4 nm.

3. Conclusion

We have proposed a vertical polarization beam splitter based on a three-port directional coupler. The central low-loss hybrid LR-SPP waveguide allowed coupling only the TM-polarization mode to the outer Si waveguides, which are configured with vertical and horizontal offsets. The coupling length is less than 10 μm and a 30 dB extinction ratio is achieved in the full C-band. The proposed optical device structure is highly compatible with the CMOS fabrication process.

References

[1] Bozhevolnyi S I, Volkov V S, Devaux E, Laluet J Y and Ebbesen T W 2006 Channel plasmon subwavelength waveguide components including interferometers and ring resonators *Nature* **440** 508–11

[2] Dai D and He S 2009 A silicon-based hybrid plasmonic waveguide with a metal cap for a nano-scale light confinement *Opt. Express* **17** 16646–53

[3] Wu M, Han Z and Van V 2010 Conductor-gap-silicon plasmonic waveguides and passive components at subwavelength scale *Opt. Express* **18** 11728–36

[4] Kim J T 2011 CMOS-compatible hybrid plasmonic waveguide for subwavelength light confinement and on-chip integration *IEEE Photon. Technol. Lett.* **23** 206–8

[5] Kim J T 2011 CMOS-compatible hybrid plasmonic slot waveguide for on-chip photonic circuits *IEEE Photon. Technol. Lett.* **23** 1481–3

[6] Dionne J, Diest K, Sweatlock L and Atwater H 2009 PlasMOStor: a metal–oxide–Si field effect plasmonic modulator *Nano Lett.* **9** 897–902

[7] Zhu S, Liow T Y, Lo G Q and Kwong D L 2011 Fully complementary metal–oxide–semiconductor compatible nanoplasmonic slot waveguides for silicon electronic photonic integrated circuits *Appl. Phys. Lett.* **98** 021107

[8] Zhu S, Lo G Q and Kwong D L 2011 Electro-absorption modulation in horizontal metal–insulator–silicon–insulator–metal nanoplasmonic slot waveguides *Appl. Phys. Lett.* **99** 151114

[9] Zhu S, Lo G Q and Kwong D L 2012 Components for silicon plasmonic nanocircuits based on horizontal $Cu--SiO_2--Si--SiO_2--Cu$ nanoplasmonic waveguides *Opt. Express* **20** 5867–88

[10] Kim J T and Park S 2013 The design and analysis of monolithic integration of CMOS-compatible plasmonic waveguides for on-chip electronic–photonic integrated circuits *J. Lightwave Technol.* **31** 2974–81

[11] Fukuda H, Yamada K, Tsuchizawa T, Watanabe T, Shinojima H and Itabashi S 2006 Ultrasmall polarization splitter based on silicon wire waveguides *Opt. Express* **14** 12401–8

[12] Dai D, Bauters J and Bowers J E 2012 Passive technologies for future large-scale photonic integrated circuits on silicon: polarization handling, light non-reciprocity and loss reduction *Light: Sci. Appl.* **1** 1–14

[13] Lou F, Dai D and Wosinski L 2012 Ultracompact polarization beam splitter based on a dielectric-hybrid plasmonic-dielectric coupler *Opt. Lett.* **37** 3372–4

[14] Chee J, Zhu S and Lo G Q 2012 CMOS compatible polarization splitter using hybrid plasmonic waveguide *Opt. Express* **20** 25345–55

[15] Guan X, Wu H, Shi Y, Wosinski L and Dai D 2013 Ultracompact and broadband polarization beam splitter utilizing the evanescent coupling between a hybrid plasmonic waveguide and a silicon nanowire *Opt. Lett.* **38** 3005–8

[16] Berini P 2000 Plasmon-polariton waves guided by thin lossy metal films of finite width: bound modes of symmetric structures *Phys. Rev.* B **61** 10484–503

[17] Kim J T, Park S, Ju J J, Park S K, Kim M and Lee M H 2007 Low-loss polymer-based long-range surface plasmon-polariton waveguide *IEEE Photon. Technol. Lett.* **19** 1374–6

[18] Chen L, Liu X B, Cao Z Q and Zhuang S L 2011 Mechanism of giant Goos–Hänchen effect enhanced by long-range surface plasmon excitation *J. Opt.* **13** 035002

[19] Palik E D (ed) 1985 *Handbook of Optical Constants of Solids* (San Diego, CA: Academic)

[20] Chen J, Li Z, Yue S and Gong Q 2009 Hybrid long-range surface plasmon-polariton modes with tight field confinement guided by asymmetrical waveguides *Opt. Express* **17** 23603–9

[21] Kim J T, Ju J J, Park S, Kim M, Park S K and Shin S Y 2010 Hybrid plasmonic waveguide for low-loss lightwave guiding *Opt. Express* **18** 2808–13

[22] Donnelly J P 1986 Limitations on power-transfer efficiency in three-guide optical couplers *IEEE J. Quantum Electron.* **22** 610–6

[23] Donnelly J P, Haus H A and Whitaker N 1987 Symmetric three-guide optical coupler with nonidentical center and outside guides *IEEE J. Quantum Electron.* **23** 401–6