Ultra-compact and -broadband integrated plasmonic waveplates with high efficiency

Hamed Pezeshki1,2

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Abstract
Ultra-compact and -broadband integrated gold plasmonic half-wave and quarter-wave plates (HWP and QWP) based on the mode interference mechanism are proposed with applications in magneto-photonics, mode- and polarization-division multiplexing. The numerical simulations based on a finite element method reveals that the proposed HWP offers a maximum polarization conversion efficiency of 99.6% at a wavelength of \(\lambda_0 = 1.55\ \mu\text{m}\) with a 1 dB bandwidth of 140 nm (\(\lambda_0 = 1.47–1.61\ \mu\text{m}\)), covering 82% of the S to L telecommunication bands. In this wavelength range, HWP has an insertion loss below 2.3 dB and an extinction ratio between 9 and 24 dB, respectively. The presented QWP functions over the C telecommunication band (\(\lambda_0 = 1.53–1.565\ \mu\text{m}\)), where the transmission contrast between its transverse magnetic and electric modes is 0±0.04. Moreover, QWP offers a polarization rotation angle in the range of 45±5° over the same wavelength range. Finally, this paper illustrates that the proposed waveplates have a robust tolerance to fabrication errors.

1 Introduction
Silicon-on-Insulator (SOI) has become a popular platform for the fabrication of low-cost and large-scale photonic integrated circuits (PICs) due to its compatibility with complementary metal-oxide-semiconductor (CMOS) process [1–3]. However, SOI-based photonic devices suffer from high polarization sensitivity due to a large index difference between the silicon (Si) waveguide and silica (SiO2) [4, 5]. Besides, many photonic devices require the control over the polarization of a propagating waveguide mode to function properly [3, 6, 7]. Therefore, designing a miniaturized integrated polarization converter to preserve the polarization diversity and/or change the polarization state of a propagating waveguide mode at will is of high significance.

During the recent decades, two major polarization conversion schemes of mode evolution and mode interference have been proposed, where devices based of the former scheme, typically made of a single photonic waveguide, require lengths of about 100 \(\mu\text{m}\) (or more) to provide adiabatic mode conversion [8–12]. In contrast, devices which use the mode interference scheme function based on the interference between the two beating waveguide modes by breaking the symmetry of the waveguide [13–15]. Majority of the reported polarization converters based on the mode interference scheme have been designed using slanted waveguides [16–18] and narrow trenches [19–21]. However, such devices require a complex fabrication process [22].

Surface plasmon polaritons (SPPs) have shown their potential in miniaturizing variety of photonic devices including half-wave and quarter-wave plates (HWP and QWP). Some of the early reported plasmonic HWPs have illustrated miniaturized footprints, but at the expense of high insertion losses of > 11 dB due to large ohmic losses imposed by SPPs [14]. Other groups have proposed the use of a low-refractive index thin spacer layer at the metal-Si interface to reduce ohmic losses by SPPs [15, 23], resulting in lower insertion losses between 2 and 5 dB, with conversion lengths of ≥ 5 \(\mu\text{m}\), respectively. Despite all the efforts, the proposed designs have failed to illustrate highly efficient compact HWPs working over a broadband wavelength range.

In parallel, there have been some reports on the design of SPP-based QWPs. Recent works on the illustration of QWPs using plasmonic metasurfaces illustrated high efficiency over a broad wavelength range. However, they function in a free space configuration [24, 25]. In addition, there...
have been some advancements in the illustration of QWPs on an integrated platform but without addressing the wavelength response of such devices [26–28]. So, according to the recent trends in implementing different functionalities on a single chip [29], it would be of great interest to present integrated plasmonic waveplates with miniaturized sizes and broadband operations.

Here, this paper presents the designs of miniaturized plasmonic HWP and QWP on a SOI platform based on the mode interference. The mode interference is provided by coupling a gold metal layer on top of a Si ridge waveguide to break the waveguide’s symmetry. Based on the simulation results using full-vectorial finite element method (FEM), the proposed HWP with a length of 3 μm has a maximum polarization conversion efficiency (extinction ratio) of $PCE = 99.6\%$ ($ER = 23.8$ dB) at a wavelength of $\lambda_0 = 1.55$ μm with $PCE \geq 90\%$ ($ER \geq 9.1$ dB) over the wavelength range of $\lambda_0 = 1.47–1.61$ μm, i.e., 82% of the S to L telecommunication bands. Moreover, HWP offers a very low insertion loss of $IL_{HL} = 1.7$ dB at $\lambda_0 = 1.55$ μm, while remains < 2.3 dB for the same wavelength range. Furthermore, the proposed QWP with a length of 1.45 μm is efficiently functional over the wavelength range of $\lambda_0 = 1.53–1.565$ μm, the C telecommunication band, while the transmission contrast between its transverse electric and magnetic modes, i.e., TE₀ and TM₀, is $0\pm 0.04$. Besides, it offers a polarization rotation angle in the range of $45\pm 5^\circ$, and has a very low insertion loss of $IL_{IL} = 2.5$ dB, across the same wavelength range. Finally, the fabrication tolerance of the proposed devices to some critical design parameters is investigated, which shows the robustness of the device designs to the considered fabrication errors. The proposed HWP and QWP with highly efficient performance over a long wavelength range can be potentially attractive in magneto-photonic devices [30, 31], mode- and polarization-division multiplexing [32, 33] and so on.

The rest of this paper is organized as follows. Section 2 presents the structure of the proposed waveplates as well as the performance results of HWP. Section 3 shows the results for the QWP’s performance. The evaluation of the fabrication tolerance of the proposed devices is presented in section 4, which is followed by a discussion in section 5. Finally, section 6 concludes the paper.

### 2 Structure and half-wave plate functionality

The schematic diagram of the proposed waveplates is shown in Fig. 1. According to this figure, a plasmonic polarization converter made of gold is coupled onto a Si waveguide on a SOI platform to break the symmetry along the Y axis. The Si waveguide has a cross section of 400x300 nm² (width, $w \times$ height, $h$), which is placed on a 3 μm thick SiO₂ buried oxide layer (BOX) and the cladding material is air. The length, width, and height of the polarization converter are $l_m = 3$ μm, $w_m = 120$ nm, and $h_m = 60$ nm, respectively. The length of HWP is equal to a half-beat length, $L_{HL} = \frac{\lambda}{2} (n_1 - n_2)$, where $n_1$ and $n_2$ are the effective refractive indices of the transverse electric and magnetic (TE₀ and TM₀) beating modes, respectively. Note that a thin silica (SiO₂) layer, with a height of $h_{sp} = 20$nm, is added on top of the Si waveguide as a spacer between the gold metal layer and the waveguide to reduce the ohmic losses imposed by gold. The refractive indices of Si, SiO₂, and gold are taken from the experimental works of Pierce et al. [34], Gao et al. [35], and Johnson et al. [36].

Three figures of merit $PCE$, $IL$, and $ER$ are defined to evaluate the performance of HWP. The incident light is coupled to a TM₀ waveguide mode, so $PCE$ can be calculated as [37]:

$$PCE = \frac{P_{TE_{out}}}{(P_{TE_{out}} + P_{TM_{out}})} \times 100,$$

where $P_{TE_{out}}$ and $P_{TM_{out}}$ are the powers of the TE₀ and TM₀ modes, respectively, at the output port of the waveguide in Watt (W). $IL_{HL}$ due to the mode conversion is defined as [22]:

$$IL_{HL} = -10 \log \left( \frac{P_{TE_{out}}}{P_{in}} \right),$$

where $P_{in}$ is the power of the TM₀ mode at the input port of the waveguide in Watt (W). Finally, $ER$, which is the ratio of the power of the TE₀ mode to the power of the TM₀ mode, is defined as [15]:

$$ER = 10 \log \left( \frac{P_{TE_{out}}}{P_{TM_{out}}} \right).$$
To evaluate the response of the proposed HWP with the above-mentioned design parameters, full-vectorial FEM method has been used. Ports have been used for launching a TM$_0$ waveguide mode, calculating and analyzing the performance of the devices. Perfectly matched layer (PML) has been used as a boundary condition to truncate the computational domain and avoid possible reflections off the boundaries interface. Free tetrahedral mesh sets with extremely fine accuracy have been used for meshing the spacer layer, converter section, and waveguide to achieve ultra-high accurate results. The minimum and maximum sizes of the mesh used for the SiO$_2$ spacer layer have been 1 nm and 40 nm, respectively. The gold metal layer has been meshed with the minimum and maximum sizes of 1.5 nm and 40 nm, respectively. In addition, the Si waveguide has been meshed with the minimum and maximum mesh sizes of 2.5 nm and 50 nm, respectively. Figure 2a shows $PCE$ and $ER$ over the wavelength range of 1.35 to 1.65 $\mu$m. As one can see, the left $Y$ axis shows the change in $PCE$, which varies between 61.8 and 99.6$\%$ over this ultra-broad wavelength range. Note that $PCE$ is greater than 90$\%$ over 82$\%$ of the S to L telecommunication bands, i.e., 1.47–1.61 $\mu$m. The right $Y$ axis in Fig. 2a shows $ER$, which is between 9.1 and 23.8 dB over the same wavelength range.

Figure 2b shows $IL_{H}$ and reflectivity of HWP. The left $Y$ axis in this figure illustrates that $IL_{H}$ is between 1.7 and 2.3 dB across the wavelength range of 1.47–1.61 $\mu$m, where at $\lambda_0 = 1.55$ $\mu$m, it has a minimum value of 1.7 dB. As shown by the right $Y$ axis of Fig. 2b, the designed HWP has a very low reflectivity between -15 and -26 dB, over the same wavelength range.

Figures 3a and 3b present the two-dimensional (2D) distributions of the electric field components $E_z$ and $E_y$ at the same wavelength range. The black arrows in (a) and (b) relate each curve to its corresponding $Y$ axis.

3 Quarter-wave functionality

The schematic of the proposed QWP is the same as the one shown in Fig. 1 with this difference that the length of the converter section is $l_m = 1.45$ $\mu$m, which is equal to the one-quarter of a beat length, i.e., $L_0\frac{\pi}{4} \times (n_1 - n_2)$. For QWP to have a reasonable functionality, ellipticity and amplitude ratio angle, i.e., polarization rotation angle, should be in the range of $1\pm0.15$ and $45\pm5^\circ$, respectively [38]. Besides, the transmission contrast between its TE$_0$ and TM$_0$ modes should be close to zero. Therefore, these figures of merit alongside $IL_{Q}$ are calculated accordingly and plotted in Fig. 4. The ellipticity is the ratio of $E_y$ to $E_z$ at the output port, i.e., $|E_y|/|E_z|$, and the polarization rotation angle can be written as [38]:

![Graph](image-url)
while ILQ for QWP reads:

$$ILQ = -10 \log \left( \frac{P_{TE_{out}} + P_{TM_{out}}}{P_{in}} \right).$$  

Figure 4a shows that the transmission contrast $T_{TE} - T_{TM}$ is $0 \pm 0.04$ and polarization rotation angle $RA$ is in the range of $45 \pm 5^\circ$, across the wavelength range of $1.53$–$1.565 \mu m$, the entire C telecommunication band. Correspondingly, the ellipticity lies in the range of $1 \pm 15$ over the same wavelength range, as shown in Fig. 4b. Based on Fig. 4b, it is also clear that the proposed QWP has a very low $ILQ$ of below $2.5$ dB in the entire C telecommunication band.
band. Therefore, one can see that the proposed QWP operates efficiently over a long wavelength range.

Figures 5a and 5b present the 2D distributions of the $E_z$ and $E_y$ cut-through the middle of the Si waveguide in the 2D XY plane for the TM$_0$ and TE$_0$ modes at $\lambda_0 = 1.55$ $\mu$m, respectively. Based on these figures, in contrast to HWP, both $E_y$ and $E_z$ are dominant after the outlined converter section, which manifests the QWP functionality. Figure 5c illustrates a 2D mode profile at the output port for the same wavelength, which clearly shows a $\frac{\pi}{4}$-radian rotation relative to the input TM$_0$ mode. Furthermore, the phase diagram of the longitudinal component of the electric field, $\angle E_x$, at the output port at $\lambda_0 = 1.55$ $\mu$m is illustrated in Fig. 5d, manifesting the existence of a $\frac{\pi}{4}$-radian phase shift between the TM$_0$ and TE$_0$ modes [27, 28].

4 Fabrication tolerance

This section presents the results on the fabrication tolerance of the proposed devices. As the functionality of the devices is tolerable of hundreds of nanometers variation in the length of the converter section, the fabrication tolerance is investigated for the variation in the thickness and width of the polarization converter at $\lambda_0 = 1.55$ $\mu$m, where we have a maximum efficiency for the proposed waveplates.

Figures 6a and 6b show the changes in PCE and ER of HWP in terms of the variation in the width ($w_m$) and height ($h_m$) of the polarization converter. Based on Fig. 6a, for a $h_m$ between 40 and 100 nm, PCE is greater than 95% and ER remains above 13 dB. As shown in Fig. 6b, for $\Delta w_m = \pm 20$ nm, the maximum drop in PCE is only 6.5%. According to the right Y axis in Fig. 6b, for $\Delta w_m = \pm 20$ nm, ER is greater than 11 dB.

The fabrication tolerance of QWP is exhibited in Fig. 7. According to Fig. 7a, for a $h_m$ from 52 to 75 nm, the transmission contrast deviates from 0 by $\pm 0.05$, while for the same range of variation in $h_m$, the change in RA remains in the acceptable range of 45±5°. As shown in Fig. 7b, for a variation in $w_m$ from 80 to $\sim$ 140 nm, the transmission contrast remains close to zero (i.e., $T_{TE} - T_{TM} \leq \pm 0.05$). It can also be seen from this figure that for the same change in $w_m$, RA is in the range of 45±5°, which ensures the QWP’s proper functionality.

Based on the results and capabilities of state of the art micro- and nano-fabrication technologies, one can see that the proposed devices posses a reasonable tolerance to structural fabrication errors. Moreover, it can be seen that the HWP functionality is more tolerable of changes in the thickness of the converter section. In contrast, QWP is more robust to changes in the width of the converter section.
Discussion

The proposed integrated hybrid HWP with a converter length of 3 μm possesses a maximum PCE and ER of 99.6% and 23.8 dB, as well as a minimum IL of 1.7 dB at λ₀ = 1.55 μm. It offers a 0.5 dB bandwidth of 140 nm covering 82% of the S to L telecommunication bands, while IL remains below 2.3 dB and ER varies between 9.1 and 23.8 dB, respectively. In addition, an integrated hybrid QWP is presented. The presented QWP has a transmission contrast of ~0 and RA in the range of 45±5°, over the entire C telecommunication band. In contrast, recent works on the illustration of integrated hybrid QWPs have not studied the frequency response of their devices [26, 27, 39]. Gao et al. theoretically presented a single-wavelength integrated hybrid QWP, where its length was 1.5 μm [26], while Liang et al. reported an integrated hybrid QWP for a polarization converter length of 2.8 μm, while the frequency response of their design was not studied [27]. Moreover, there have been some reports on the design of an integrated QWP based on aluminum-gallium-arsenide (AlGaAs) [28] and graphene [39] platforms. However, both designs have very long converter sections of ~53 μm and 145 μm respectively, while the latter was functioning at a very long wavelength of 100 μm. In contrast, the proposed QWP in this paper not only benefits from a miniaturized size relative to the recent reports, but also offers a broadband operation.
The performance of the introduced HWP from the perspectives of PCE, ER, and frequency response has shown improvements compared to recent works [14, 15, 22, 23, 40–43]. The presented works in [14, 15, 23] reported integrated hybrid HWPs, however with ER ≤ 15 dB and IL ≥ 2.1 dB. The hybrid HWP reported by Xu et al. [40], offers IL of 0.86 dB at the expense of much longer length (≥ 11 μm). Besides, their HWP is based on slot waveguides, while most PIC circuits use SOI ridge waveguides, i.e., wire waveguides. In fact, the use of slot waveguides might cause some practical limitations since it needs interconnects to provide mode conversion between slot and wire waveguides, resulting in additional loss. The recent work by Bai et al. [41], offers a comparable PCE with a maximum ER of 20.6. However, it has a 0.5 dB bandwidth of only 80 nm. A recent work of Tuniz et al. [42] included a design of hybrid HWP with a maximum PCE of 58% for a plasmonic polarization converter length of 4 μm. Very recently, Zhao et al. presented an integrated HWP based on the lithium-niobate-on-insulator platform. Despite its very large ER of ~ 60 dB, its silver converter section has a length of 13.7 μm which can introduce excessive ohmic losses (that may influence the response of other devices on PICs) due to high absorption loss by silver. Besides, silver has larger extinction coefficient than gold which means silver can result in more absorption loss in PICs than gold. From the fabrication perspective, silver also suffers from need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

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Declarations

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6 Conclusion

Ultra-compact and ultra-broadband integrated plasmonic waveplates functioning as HWP and QWP are proposed. The proposed waveplates work based on the mode interference by coupling a gold metal layer to a single mode SOI ridge waveguide. The FEM simulations illustrated that the proposed HWP offers a highly efficient PCE of ≥ 90% over 82% of the S to L telecommunication bands, while IL remains below 2.3 dB across the above-mentioned wavelength range. In addition, the designed QWP functions efficiently over the entire C telecommunication band, with a RA and transmission contrast of 45±5° and 0±0.04, respectively. Furthermore, it has been illustrated that the proposed waveplates have a great tolerance to fabrication errors, which make them potentially attractive for applications such as magneto-photonics, mode- and polarization-division multiplexing.

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