Integrated optical circuits combined with fibers require the control of the light polarization state (TE or TM), the so-called polarization diversity [1,2]. A polarization rotator is a key component in any polarization diversity scheme. However, designing an integrated and compact low-loss rotator has been an ongoing challenge [3–7]. So far, most designs have been based on adiabatic mode evolution [5,6] or mode interference [3,4,7]. Both methods come with their own advantages and limitations; for instance, devices based on mode interference have a short length (~10 μm), but are sensitive to fabrication imperfections and often have a limited spectral bandwidth (~25 nm) [4]. On the other hand, mode evolution devices require rather long lengths (>100 μm) to achieve sufficient extinction ratios. Furthermore, they usually require uncommonly thick silicon waveguides [6] or additional material layers [5].

Recently, the use of surface plasmon polaritons (SPPs) has been suggested to reduce the length of polarization rotators [8,9] while having a large spectral bandwidth. For example, Zhang et al. demonstrated an ultracompact rotator (3 μm) based on SPPs; however, their design showed high insertion loss (>11 dB) [8].

Here we experimentally demonstrate a polarization rotator based on a hybrid plasmonic (HP) waveguide, which we had proposed recently [10]. The HP waveguide uses a low refractive index spacer (e.g., silica) between a high-index guiding material (e.g., silicon) and metal (e.g., silver). The HP waveguide hybridize the dielectric mode of a high-index material and the SPP mode of a metal/dielectric interface [11]. HP waveguides and devices realized with them offer a good compromise between the confinement of the SPP and the low loss of dielectric waveguides. They were first introduced by Alam et al. [11,12]. Since its invention, a number of devices have been proposed [13–15] and realized [16,17] using HP waveguides.

A schematic of the realized polarization rotator is shown in Fig. 1. The top view in (a) shows three sections of the device: a short input taper, the rotation section, and a purely dielectric output taper. A silica spacer layer (omitted in Fig. 1 for clarity) separates the silver from the silicon throughout the device. A short input taper (650 nm) transforms the TM silicon waveguide mode into an HP mode. The metallic layer (silver) needed for the HP mode is introduced in this section. The estimated losses (based on FDTD simulations) due to the abrupt transitions leading to reflections and scattering are found to...
be less than 0.2 dB. In the first section, the silicon waveguide is also tapered from the original width of 450 nm to a width of 180 nm. The tapering will move the majority of the mode energy out of the silicon into the SiO$_2$ spacer region between the silicon and silver. The localization of the mode closer to the metal increases the efficiency of the rotation taking place in the second section. This second section, the rotation section, is where the silver layer on top of the waveguide is tapered sideways relative to the silicon nanowire. At the end of the rotation section, the silver is only located on the side of the silicon waveguide and not on top of it. The electric field stays orthogonal to the metal surface; thus, when the silver is tapered away from the top of the waveguide, the input TM mode of the waveguide is rotated into a TE mode. In the last section of our device, the silver is terminated, and the silicon waveguide linearly tapers out to its original width of 450 nm over a length of 1.5 μm.

The device principle was previously proposed in [10], and different device dimensions were studied. However, here due to fabrication constraints, the design is slightly altered to the one shown in Fig. 1. The main difference in the current design is that the silver is introduced on the top and on the side directly in the taper section. Previously, the silver was first only located on the top and then moved to one of the sides [10]. The advantage of the new design is that it requires less precision in alignment between the silicon and silver layer, and thus it allows for easier fabrication.

The design of the new HP rotator was optimized using an FDTD code (Lumerical) [18] and for different key geometrical dimensions. These include the length of the input and output taper, the width of the silicon waveguide at the beginning and end of the rotation section, and the spacer thickness between the silicon waveguide and the metal, in addition to the length of the rotation section. The result of the spacer thickness and rotation section length optimization is shown in Fig. 2. The insertion loss and the extinction ratio are plotted as a function of length of the rotation section for different spacer thicknesses. The losses of the device show three distinct regions: (I) short rotor length (<2 μm), the mode is not adiabatically rotated, and, thus, power is nonreversibly coupled to free space and other modes; (II) the optimal device length region with high device performance; (III) long rotor lengths (>5 μm), the mode conversion will suffer from material losses due to the metal (silver). The optimal length (II) depends on the silica spacer thickness; a larger silica thickness will move this region toward a longer length, but is approximately between 2 and 5 μm. We fabricated devices with rotation section lengths between 1 and 5 μm and a silica spacer thickness of 140 nm. This choice of silica thickness offers a good compromise between a short device length and good device performance.

The processing steps to fabricate the HP rotator shown in Fig. 1 are as follows. Gold alignment markers were deposited on a silicon-on-insulator wafer with a top silicon thickness of 220 nm and a buried oxide layer of 2 μm to allow for alignment between the silicon and metal layer. An electron beam wrote the pattern for the silicon waveguide into a spin-coated layer of ZEP-520A electron beam resist. The pattern was then transferred into the top silicon layer using a reactive ion etcher with SF$_6$/O$_2$ etch chemistry. On top of the silicon waveguide, a silica spacer layer with a thickness of 140 nm was deposited using a plasma enhanced chemical vapor deposition. The silver layer pattern was then written into a double electron beam resist stack of MMA-EL 11 and PMMA A3. The two resists combination is used to create a double lift-off cross section for a better pattern transfer. The metal was deposited in an electron beam-evaporator, and the resists were removed in Acetone. A scanning electron microscope picture of the device with the final silver layer is shown in Fig. 1(c). Before measurements, we coated the samples with a commercially available flowable oxide (FOx-15).

Figure 3(a) shows the linear setup used to illuminate the samples. A Thorlabs broadband superluminescent diode (S5FC1005S) is used to characterize the fabricated devices, where a polarizer sets the input polarization state to TM. A free-space coupling setup is used to couple the light into and out of the silicon waveguides. A polarizer separates the two output polarizations to be measured separately. An Agilent optical spectrum analyzer (AQ6317B) is used to measure the transmitted light. To account for losses in the experimental setup, as well as coupling and propagation losses of the silicon waveguides, we fabricated a number of silicon waveguides without the polarization rotator. We calculated the transmission for the HP rotators according to

$$T = \frac{2P_{\text{Rot}}^\text{TM→TE}}{P_{\text{WG}}^\text{TM} + P_{\text{WG}}^\text{TE}}.$$  

Here, $T$ is the transmission of our polarization rotator, $P_{\text{Rot}}^\text{TM→TE}$ is the measured transmitted power of one waveguide with a polarization rotator for TM polarized input light to TE output light, and $P_{\text{WG}}^\text{TM,TE}$ is the averaged transmitted power of silicon waveguides without polarization.
rotators for the TM and TE polarization, respectively. The factor of 2 in the numerator is due to the normalization of the silicon waveguides; the power of the two polarizations is accounted for by half. The polarization extinction ratio was calculated according to

$$\text{PER} = \frac{P_{\text{Rot, TM}}}{P_{\text{Rot, TM}} - P_{\text{Rot, TE}}} \cdot \frac{P_{\text{WG, TM}}}{P_{\text{WG, TE}}} \cdot 2 \cdot \frac{P_{\text{WG, TM}}}{P_{\text{WG, TE}}} \cdot (2)$$

where PER is the polarization extinction ratio of the TM polarization, and $P_{\text{Rot, TM}}$ is the measured transmitted power for TM polarized input to TM output polarization with polarization rotator.

The measured insertion loss $[-10 \log_{10}(T)]$ and polarization extinction ratio $[-10 \log_{10}(\text{PER})]$ as a function of wavelength are plotted in Fig. 3(b). The spectrum is shown for a device with a rotation section length of 3.7 μm. After including tapers, the total device length is 5.85 μm for this device. Our rotator shows a truly broadband response with an insertion loss below 3.5 dB for more than a 90 nm bandwidth around 1.55 μm and a polarization extinction ratio >7 dB for the same wavelength range.

The insertion loss at a wavelength of 1.55 μm, as a function of the length of the rotation section, for a number of fabricated rotators is plotted in Fig. 4 (bottom) for $\lambda = 1.55$ μm. A minimum insertion loss of 1.5 dB is reached for a rotation section length of 2.3 μm. We have also plotted the simulation results for the spacer thickness of 140 nm to compare it with the experimental results; both simulation and experimental results show very good agreement. The polarization extinction ratio of the TM-polarization is plotted in Fig. 4 (top). It reaches a maximum of 13.5 dB for a rotation section of 3.7 μm length. Shorter devices (<2 μm) show worse performance (smaller extinction ratio, higher insertion loss); this is due to the fact that the device is too short to rotate the mode adiabatically; thus a significant part of the light remains in the input polarization state (TM). Moreover, for longer devices (>4 μm), the propagation losses due to the metal becomes significant, which increases the insertion loss and reduces the extinction ratio.

The uncertainty introduced due to the normalization using the silicon waveguides without a rotator is estimated as follows: the standard deviation of the silicon waveguide transmission spectra without a rotator was first calculated; the uncertainty in the insertion loss as well as the extinction ratio was then calculated using uncertainty propagation. The uncertainty varies slightly for different lengths, but it is around 2 dB for all devices; this is due to the rather large fabrication variations we experience in our facility. However, even in the worst-case scenario, in which the actual insertion loss is on the higher end of the uncertainty range, our devices still show very good performance.

In summary, we have experimentally demonstrated an ultracompact HP polarization rotator. The rotator has a polarization extinction ratio of >13.5 dB and a low insertion loss of 2 dB. Over a spectral bandwidth of >90 nm around 1.55 μm, the insertion loss stays below 3.5 dB, and the polarization extinction ratio is above 7 dB for the same wavelength range. The total device length is
5.85 μm (3.7 μm rotation section + 2.15 μm tapers). Our realized rotator achieves significant reduction in the losses compared to previously reported surface plasmon rotators [8]. The realized rotator is also more than an order of magnitude shorter than purely dielectric-based devices [5] while having comparable transmission and extinction ratios.

We thank A. Tsukernik for advice and help with the fabrication of the samples. This work was supported by NSERC Discovery Grant and the NSERC Strategic Network for Bioplasmonic Systems.

References