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Integrated photonic polarizers with 2D reduced graphene oxide

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Optical polarizers, which allow the transmission of specific polarization states, are essential components in modern optical systems. Here, we experimentally demonstrate integrated photonic polarizers incorporating reduced graphene oxide (rGO) films. 2D graphene oxide (GO) films are integrated onto silicon waveguides and microring resonators (MRRs) with precise control over their thicknesses and sizes, followed by GO reduction via two different methods including uniform thermal reduction and localized photothermal reduction. We measure devices with various lengths, thicknesses, and reduction degrees of GO films. The results show that the devices with rGO exhibit better performance than those with GO, achieving a polarization-dependent loss of ~47 dB and a polarization extinction ratio of ~16 dB for the hybrid waveguides and MRRs with rGO, respectively. By fitting the experimental results with theory, it is found that rGO exhibits more significant anisotropy in loss, with an anisotropy ratio over 4 times that of GO. In addition, rGO shows higher thermal stability and greater robustness to photothermal reduction than GO. These results highlight the strong potential of rGO films for implementing high-performance polarization selective devices in integrated photonic platforms.

Keywords: integrated optics; 2D materials; graphene oxide; optical polarizers

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Introduction

In modern optical systems, controlling light polarization is of fundamental importance and underpins a variety of advanced optical technologies^{1–3}. Optical polarizers, which transmit light with a certain polarization state while blocking light in the orthogonal polarization state, serve as essential components for controlling light polarization⁴. To date, a wide range of optical polarizers have

been implemented based on birefringent crystals^{5,6}, optical fibers^{7,8}, refractive prisms^{9,10}, and integrated photonic devices^{11–13}. However, these polarizers made from bulk materials typically face challenges in achieving effective polarization selection across broad wavelength ranges^{1,14,15}, despite the growing demand for broadband optical polarizers driven by rapid advancements in photonic technologies and systems^{16,17}.

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Since the groundbreaking isolation of graphene in 2004¹⁸, there has been an enormous surge in research on two-dimensional (2D) materials with atomic-scale thicknesses, which exhibit many extraordinary properties unattainable for conventional bulk materials^{19–21}. With highly anisotropic properties across wide optical bands, 2D materials such as graphene^{15,22,23}, graphene oxide (GO)^{24–26}, and transition metal dichalcogenides (TMDCs)^{27–29} have been incorporated into bulk material device platforms to implement high-performance optical polarizers. As an oxidized derivative of graphene, GO has facile solution-based synthesis processes as well as transfer-free film coating on dielectric substrates with precise control over the film thickness, making it well-suited for large-scale on-chip integration to implement hybrid devices^{30–32}. In addition, the properties of GO can be easily changed through various reduction methods, providing a high flexibility to optimize the performance of hybrid devices^{33–36}.

Previously, we demonstrated integrated optical polarizers incorporating 2D GO films on both doped silica and silicon device platforms^{24,25}. In this work, we integrate 2D reduced graphene oxide (rGO) films onto photonic chips to implement waveguide and microring resonator (MRR) polarizers with improved performance. We fabricate hybrid integrated devices with precise control of the GO film thicknesses and lengths. The reduction of GO is achieved by using two methods: uniform thermal reduction, achieved by heating the entire integrated chip on a hot plate, and localized photothermal reduction, induced by high power of input light. Detailed measurements are carried out for devices with various GO film lengths, thicknesses, and reduction degrees. The results show that the devices with rGO exhibit better polarization selectivity than comparable devices with GO. Up to ~47 dB polarization-dependent loss (PDL) and ~16 dB polarization extinction ratio (PER) are achieved for the hybrid waveguides and MRRs with rGO, respectively. By fitting the experimental results with theoretical simulations, we find that rGO exhibits significantly improved loss anisotropy, with an anisotropy ratio more than 4 times that of GO. Compared to GO, rGO also exhibits stronger thermal stability and lower sensitivity to photothermal reduction. These results verify the effectiveness of on-chip integration of 2D rGO films to realize high performance optical polarizers.

Results and discussion

Device design and fabrication

As an oxidized derivative of graphene, monolayer GO features a carbon network attached with different kinds of oxygen functional groups (OFGs), such as hydroxyl, epoxide, carbonyl, and carboxylic groups^{33,37,38}. Figure 1(a) illustrates the atomic structures of GO, semi-reduced GO (srGO), and highly reduced GO (hrGO), together with the corresponding Dirac cones illustrating their optical bandgaps. Due to the existence of isolated sp^2 domains within the sp^3 carbon-oxygen matrix, unreduced GO is a dielectric material with a large optical bandgap of ~2.1–3.6 eV^{37,39}, which allows for very low linear light absorption as well as two-photon absorption in the infrared wavelength region. The reduction of GO can break the chemical bonds between the carbon network and the OFGs. Compared to pristine GO, rGO has a decreased bandgap^{40,41}, resulting in alterations to material properties such as optical absorption, refractive index, and electrical conductivity.

Practically, GO film reduction can be achieved by using different methods, such as thermal reduction, chemical reduction, and photoreduction^{42–44}. As the degree of reduction rises, the fraction of sp^2 -hybridized carbon atoms increases due to removal of the OFGs and reconstruction of the sp^2 carbon network. According to ref.⁴⁵, the fraction of sp^2 -hybridized carbon atoms increased from ~5% to ~31% after reduction under air at 150 °C and remained relatively stable at ~27% when further annealed at 300 °C⁴⁵. It is also worth noting that although thermal reduction can remove most OFGs by further increasing the temperature, it cannot entirely remove all OFGs, as C=O bonds are stronger than C-C bonds in the sp^2 carbon network⁴⁶. For hrGO with minimal remaining OFGs, the bandgap and material properties closely resemble those of graphene, which exhibits a zero bandgap and metallic behaviour^{47–49}.

Figure 1(b) shows the schematic of an integrated waveguide polarizer based on a silicon photonic waveguide coated with a 2D GO film. The cross section of the silicon waveguide is 400 nm × 220 nm. The GO film has a thickness of 4 nm, which corresponds to 2 layers of GO fabricated using a solution-based self-assembly method (as discussed later in this section). Figure 1(c) shows the corresponding transverse electric (TE) and transverse magnetic (TM) mode profiles for the hybrid waveguide in Fig. 1(b), which were obtained using a commercial

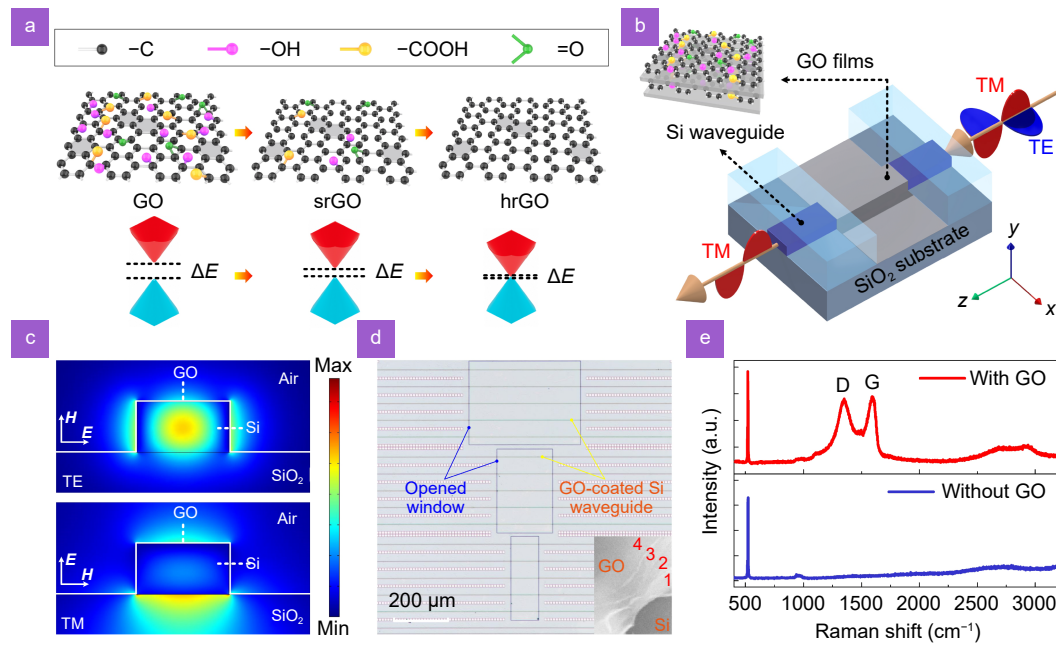


Fig. 1 | (a) Schematics of atomic structures and bandgaps of graphene oxide (GO), semi-reduced GO (srGO), and highly reduced GO (hrGO). (b) Schematic illustration of a GO-coated silicon waveguide as an optical polarizer. Inset illustrates the layered GO film structure fabricated by self-assembly. (c) TE and TM mode profiles for the hybrid waveguide with 2 layers of GO. (d) Microscopic image of a GO-coated silicon-on-insulator (SOI) chip with opened windows. Inset shows a scanning electron microscopy (SEM) image of the layered GO film, where numbers (1–4) refer to the number of layers for that part of the image. (e) Measured Raman spectra of the SOI chip in (d) without GO and with 2 layers of GO.

mode-solving simulation software (COMSOL Multiphysics). The TE- and TM-polarized effective indices (at 1550 nm) for the hybrid waveguide were $(2.093 + 1.244 \times 10^{-4}i)$ and $(2.093 + 4.784 \times 10^{-5}i)$, respectively. In our simulation, the refractive index (n) and extinction coefficient (k) of GO for TE polarization were $n_{\text{TE}} = \sim 1.969$ and $k_{\text{TE}} = \sim 0.0098$, respectively. For TM polarization, the corresponding values were $n_{\text{TM}} = \sim 1.898$ and $k_{\text{TM}} = \sim 0.0022$. The n , k values were obtained from our previous measurements in ref.³⁴ and the experimental results in following sections. The large difference between k_{TE} and k_{TM} is due to the significant anisotropy in the light absorption of 2D GO films, where the in-plane absorption is much stronger than the out-of-plane absorption^{15,24}. As a result, TE-polarized (in-plane) light experiences a higher loss compared to TM-polarized (out-of-plane) light as it propagates through the hybrid waveguide, allowing the hybrid waveguide to perform as a TM-pass optical polarizer.

Figure 1(d) shows a microscopic image of a silicon-on-insulator (SOI) chip coated with 2 layers of GO, with the inset showing a scanning electron microscopy (SEM) image of the layered GO film. The silicon waveguides on this chip were patterned using 248-nm deep ultraviolet lithography, followed by inductively coupled plasma

etching. After this, a 1.5- μm -thick silica layer was deposited by plasma enhanced chemical vapor deposition to cover the SOI chip as an upper cladding. To enable the interaction between the GO films and the evanescent field⁵⁰ from the silicon waveguides, windows were opened on the silica upper cladding to enable the coating of 2D GO films onto the silicon waveguides. In our fabricated devices, all silicon waveguides have a length of ~ 3.0 mm, and the lengths of the opened windows ranged between ~ 0.1 mm and ~ 2.2 mm.

The coating of the GO film was achieved by using a solution-based self-assembly method that enabled transfer-free and layer-by-layer film coating^{24,30}. First, a GO solution composed of negatively charged GO nanoflakes synthesized through the modified Hummers methods was prepared³⁵. Next, the SOI chip with a negatively charged surface was immersed in a positively charged polymer solution to obtain a polymer-coated integrated chip with a positively charged surface. Finally, the polymer-coated integrated chip was immersed in the prepared GO solution, where a GO monolayer was formed onto the top surface through the self-assembly of exfoliated GO nanoflakes. By repeating the above processes, a multi-layer film structure composed of alternating GO layers and oppositely charged polymer layers was

constructed via electrostatic forces, with the GO layers formed through the self-assembly of exfoliated GO nanoflakes. As compared with the complicated film transfer methods employed for other 2D materials such as graphene and TMDCs^{51,52}, this coating method enables transfer-free coating process and precise control of the film thickness. In addition, it allows conformal coating of 2D GO films onto silicon waveguides with minimal air gaps⁵³. In Fig. 1(d), the coated GO film shows high transmittance and good morphology without any noticeable wrinkling or stretching, confirming excellent film attachment onto the silicon waveguides. According to our previous atomic force microscopy measurements of GO films prepared using the same method⁵⁴, the as-prepared GO films had an average thickness of ~ 2 nm per layer.

Figure 1(e) shows the measured Raman spectra of the SOI chip in Fig. 1(d) before and after coating 2 layers of GO, which were measured using a ~ 514 nm pump laser. In the measured Raman spectrum for the GO-coated chip, the existence of the featured D (~ 1345 cm^{-1}) and G (~ 1590 cm^{-1}) peaks^{55–57} provides evidence for successful integration of 2D GO film onto the SOI chip.

Polarization-dependent loss measurements

In Fig. 2, we present the measured insertion losses (IL s) of our fabricated devices for input continuous-wave (CW) light in different polarization states. We performed measurements for devices with various GO film lengths (L_{GO}) and GO layer numbers (N), after being subjected to various reduction temperatures (T_{R}). Here we chose the temperature range of $50\text{ }^{\circ}\text{C} \leq T_{\text{R}} \leq 200\text{ }^{\circ}\text{C}$ because the polymer layers in the self-assembled films cannot withstand temperatures beyond $200\text{ }^{\circ}\text{C}$. For all the devices, the cross section of the uncoated silicon waveguides was $\sim 400\text{ nm} \times 220\text{ nm}$. In our measurements, lensed fibers were used to butt couple a CW light at ~ 1550 nm into and out of the fabricated devices, which had inverse-taper couplers at both ends. The fiber-to-chip coupling loss was ~ 5 dB / facet. For comparison, we measured the IL s by using the same input power of ~ 0 dBm. Unless otherwise specified, the input power (P_{in}) and IL in our following discussion refers to the values after excluding the fiber-to-chip coupling loss.

Figure 2(a-i) and 2(a-ii) plot the measured TE- and TM-polarized IL versus L_{GO} for the hybrid waveguides with 1 layer of GO ($N = 1$), respectively. Before the IL measurement, the SOI chip was heated on a hot plate for

15 minutes at various temperatures T_{R} . For comparison, the results corresponding to different T_{R} are plotted together with those measured at room temperature prior to heating (which are labeled as 'initial'). In each figure, the data points represent the average values from measurements of three duplicate devices, and the error bars reflect the variations across different samples. We do not show results for $IL > 70$ dB in these and subsequent figures because it exceeds the detection range of the optical power meter used in our measurements.

In Fig. 2(a-i) and 2(a-ii), the IL increases with L_{GO} for both TE and TM polarizations, with the former exhibiting a more dramatic increase than the latter. At $T_{\text{R}} = \sim 50\text{ }^{\circ}\text{C}$, both the TE- and TM-polarized IL exhibited no significant differences as compared with that at the initial unheated status. These results suggest that there were no significant changes in the GO film properties at $T_{\text{R}} = \sim 50\text{ }^{\circ}\text{C}$, indicating that the reduction of GO did not occur at this temperature. In contrast, when $T_{\text{R}} \geq \sim 100\text{ }^{\circ}\text{C}$, the IL increases with T_{R} for both TE and TM polarizations. This reflects the loss increase caused by GO reduction at high temperatures. As T_{R} increases, a higher degree of reduction was achieved, leading to a more significant increase in the IL .

Figure 2(a-iii) shows the corresponding PDL (dB) obtained by subtracting the TM-polarized IL in Fig. 2(a-ii) from the TE-polarized IL in Fig. 2(a-i). The PDL increases with L_{GO} , and it also increases with T_{R} when $T_{\text{R}} \geq 100\text{ }^{\circ}\text{C}$. For the device with $L_{\text{GO}} = \sim 0.4$ mm and at $T_{\text{R}} = \sim 200\text{ }^{\circ}\text{C}$, a maximum PDL value of ~ 47 dB was obtained. In contrast, the PDL exhibited no significant difference between the initial status and at $T_{\text{R}} = 50\text{ }^{\circ}\text{C}$, achieving a PDL of ~ 1 dB for the devices with the same L_{GO} . By further increasing L_{GO} for devices with hrGO (i.e., at $T_{\text{R}} = \sim 150$ and $\sim 200\text{ }^{\circ}\text{C}$), a PDL exceeding ~ 47 dB can be achieved (not shown in this figure due to limited detection range of the optical power meter), at the expense of a higher additional IL induced by GO.

Figure 2(b-i) and 2(b-ii) plot the measured IL versus T_{R} for TE and TM polarizations, respectively. Here we provide results for the hybrid waveguides with 1 and 2 layers of GO. For comparison, all the devices had the same $L_{\text{GO}} = \sim 0.4$ mm. Both the TE- and TM-polarized IL remains unchanged when $T_{\text{R}} \leq \sim 50\text{ }^{\circ}\text{C}$. For $T_{\text{R}} \geq \sim 100\text{ }^{\circ}\text{C}$, the TE-polarized IL shows a more obvious increase with T_{R} than that for TM polarization, following a trend similar to that in Fig. 2(a-i) and 2(a-ii). Compared to the devices with 1 layer of GO ($N = 1$), higher IL was

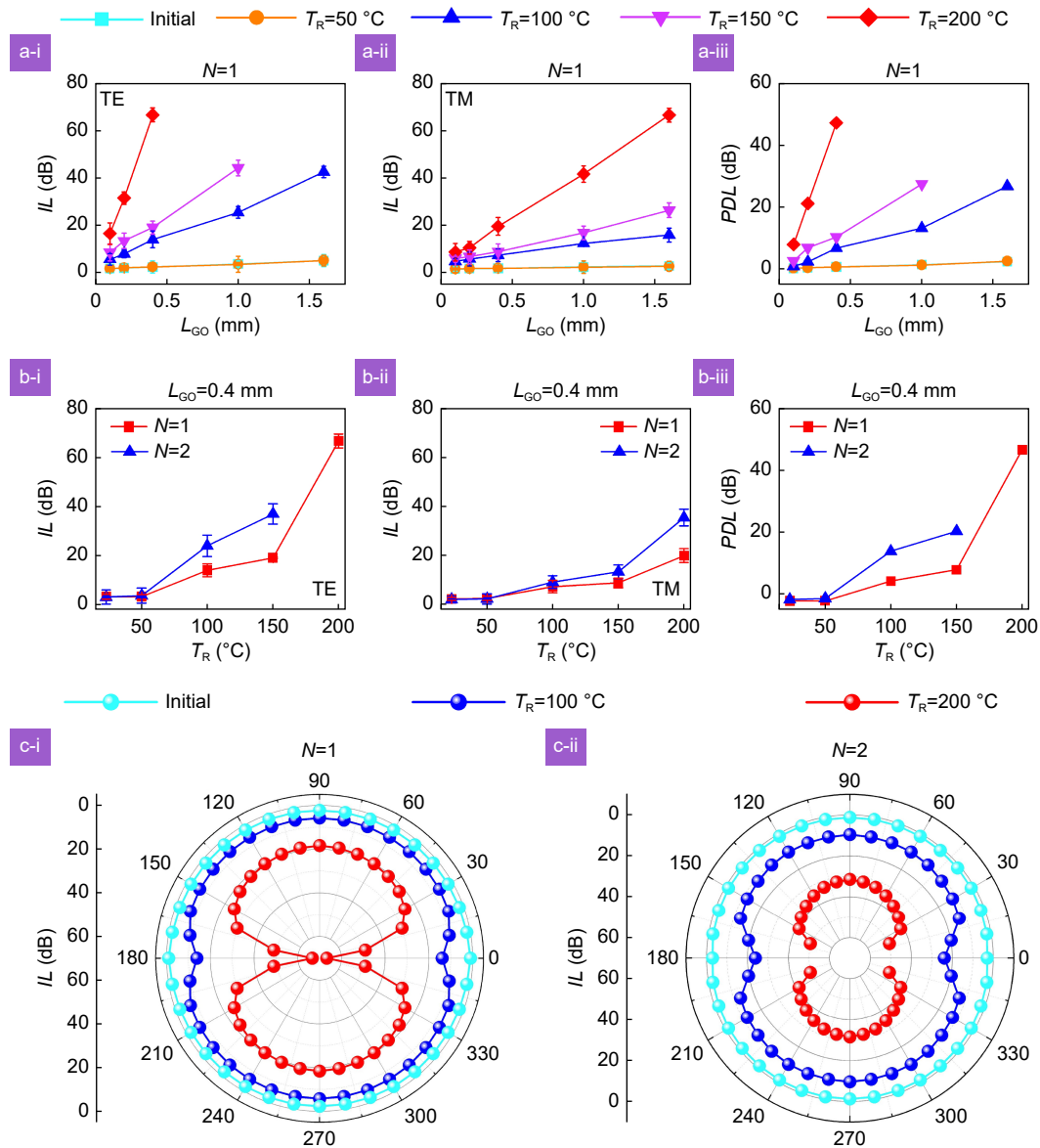


Fig. 2 | (a) Measured insertion loss (IL) versus GO film length (L_{GO}) for the hybrid waveguides with a monolayer GO film ($N=1$) after the chip was heated at various temperatures T_R . (b) Measured IL versus T_R for the waveguides with 1–2 layers of GO ($N=1, 2$). In (a) and (b), (i) and (ii) show the corresponding results for TE and TM polarizations, respectively. (iii) shows the polarization dependent loss (PDL) calculated from (i) and (ii). (c) Polar diagrams for the measured IL of devices with (i) 1 and (ii) 2 layers of GO after the chip was heated at various temperatures T_R . In (a–c), the input continuous-wave (CW) power and wavelength were ~ 0 dBm and ~ 1550 nm, respectively. In (b) and (c), $L_{GO} = \sim 0.4$ mm.

achieved for the devices with 2 layers of GO ($N=2$), reflecting a higher loss induced by a thicker GO film. Figure 2(b-iii) shows the corresponding PDL extracted from the measured IL , where higher PDL values were also achieved for the waveguides with thicker GO films. For the 2-layer device at $T_R = \sim 150^\circ\text{C}$, the PDL was ~ 24 dB, in contrast to ~ 10 dB for a comparable 1-layer device. At $T_R = \sim 200^\circ\text{C}$, it is anticipated that the 2-layer device can achieve a high PDL exceeding 60 dB, we were not able to measure it due to the limited detection range of our opti-

cal power meter.

Figure 2(c-i) and 2(c-ii) show the polar diagrams for the measured IL of devices with 1 and 2 layers of GO ($N=1, 2$), respectively. In each figure, we plot three curves corresponding to different T_R . For comparison, all the hybrid waveguides had the same $L_{GO} = \sim 0.4$ mm. The polar diagrams show variations in IL values across different polarization angles, which reflects the polarization selectivity of the hybrid waveguides. For the waveguides with 1 layer of GO, the PDL values at the initial unheated

status, $T_R = \sim 100^\circ\text{C}$, and $T_R = \sim 200^\circ\text{C}$ are ~ 1 dB, ~ 7 dB, and ~ 47 dB, respectively. These results indicate that the polarization selectivity is improved as the degree of GO reduction increases. At $T_R = \sim 100^\circ\text{C}$, the *PDL* values for $N = 1$ and $N = 2$ are ~ 7 dB and ~ 15 dB, respectively. This reflects that improved polarization selectivity can also be achieved for the device with a thicker GO film.

Analysis of GO film properties

By fitting the experimental results in Fig. 2 with theoretical simulations, we further analyze the properties of 2D GO films. Figure 3(a) shows the waveguide propagation loss (*PL*) versus T_R for the hybrid devices with 1 and 2 layers of GO (i.e., $N = 1, 2$), which was extracted from the measured *IL* in Fig. 2(b). The excess propagation loss (*EPL*) induced by the GO films was further calculated by excluding the *PL* for the uncoated silicon waveguide (i.e., ~ 3.4 dB/cm and ~ 3.1 dB/cm for TE and TM polarizations, respectively). The TE-polarized *EPL* induced by 1 layer of rGO at $T_R = 200^\circ\text{C}$ was ~ 1520 dB/cm, in contrast to ~ 20 dB/cm for 1 layer of unreduced GO at the initial status. This reflects the substantial increase in loss for highly reduced GO films. We also note the value of ~ 1520 dB/cm is lower than the typical values of *EPL* in-

duced by monolayer graphene (i.e., ~ 2000 dB/cm^{58,59}). This suggests that, although the GO film was highly reduced at $T_R = 200^\circ\text{C}$, it was not yet completely reduced.

Figure 3(b) shows the extinction coefficients (k 's) of GO obtained by fitting the results in Fig. 3(a) with optical mode simulations (at 1550 nm) for the hybrid waveguides. For 1 layer of rGO at $T_R = \sim 200^\circ\text{C}$, the value of k is ~ 0.7057 for TE polarization, which is about 75 times that of comparable unreduced GO. For all different N and T_R , the GO films exhibited larger values of k for TE polarization as compared to TM polarization, reflecting the intrinsic anisotropy in the loss of 2D GO films. We also note that, for both polarizations, slightly higher k values were obtained with thicker GO films. This is likely due to the increased scattering loss caused by film unevenness and accumulation of imperfect layer contact in thicker films.

In Fig. 3(c), we further plot the anisotropy ratios defined as the ratios of the corresponding k values for TE- and TM- polarizations (k_{TE} / k_{TM}) in Fig. 3(b). Compared to unreduced GO, larger values of the anisotropy ratio are obtained for rGO at $T_R \geq 100^\circ\text{C}$, with the anisotropy ratio increasing for a higher degree of reduction. For 1 layer of rGO at $T_R = \sim 200^\circ\text{C}$, the anisotropy

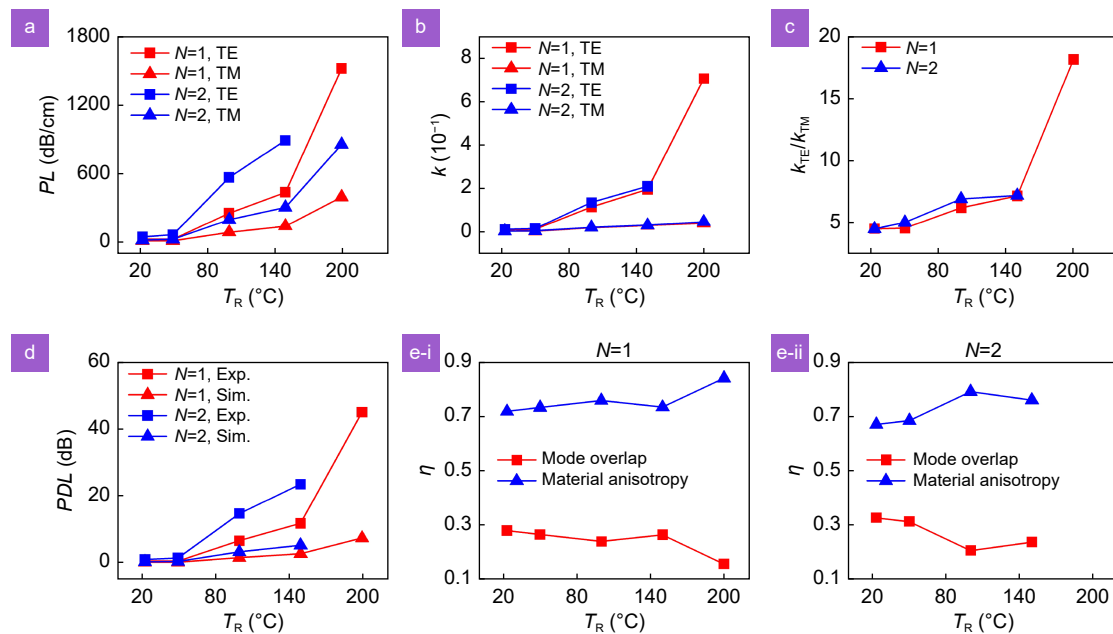


Fig. 3 | (a) TE- and TM-polarized propagation loss (*PL*) versus T_R for the hybrid waveguides with 1 and 2 layers of GO ($N = 1, 2$). (b) Extinction coefficients (k 's) of 2D GO films versus T_R obtained by fitting the results in (a) with optical mode simulations. (c) Anisotropy ratios of k values for TE and TM polarizations (k_{TE} / k_{TM}) extracted from (b). (d) Measured (Exp.) and simulated (Sim.) *PDL* versus T_R for the waveguides with 1–2 layers of GO ($N = 1, 2$). The simulated *PDL* values were obtained by using the same k value for both TE and TM polarizations. (e) Fractional contributions (η 's) to the overall *PDL* from polarization-dependent mode overlap and material loss anisotropy, which were extracted from (d). (e-i) and (e-ii) show the results for $N = 1$ and 2, respectively.

ratio is ~ 18 – over 4 times higher than that of 1 layer of unreduced GO. These results highlight an interesting phenomenon that the 2D GO films exhibit more significant loss anisotropy as the degree of reduction increases. This is probably because GO reduction leads to the removal of OFGs and hence a decrease in the film thickness. We also note that in ref.¹⁵ monolayer graphene (with a thickness of ~ 0.5 nm, in contrast to ~ 2 nm for monolayer unreduced GO) exhibits a higher anisotropy ratio of ~ 30 . This suggests that highly reduced GO exhibits loss anisotropy close to that of graphene.

Compared to GO, the higher anisotropy ratio of rGO leads to more significant difference between the absorption of in-plane and out-of-plane light waves, making it better suited for implementing optical polarizers with high polarization selectivity. In addition, unlike the intricate film transfer methods needed for on-chip integration of graphene, GO offers advantages for large-scale manufacturing due to its facile solution-based synthesis processes and transfer-free film coating. Hybrid integrated devices with rGO can be readily fabricated by further reducing GO within the hybrid devices. Therefore, the GO fabrication techniques can be leveraged for large-scale manufacturing of hybrid integrated devices with rGO.

In Fig. 3(c), slightly increased anisotropy ratio is also achieved for thicker GO films. For unreduced GO, the anisotropy ratios are ~ 4.4 and ~ 4.5 for the 1 layer and 2 layer films, respectively. For 1 layer of rGO at $T_R = \sim 100$ °C, the anisotropy ratio is ~ 6 , in contrast to ~ 7 for 2 layers of rGO at that same T_R . These results reflect that the thicker film exhibits more significant anisotropy in loss for both GO and rGO.

In Fig. 3(d), we compare the measured *PDL* values with those obtained from optical mode simulations. We show the results at various T_R for the hybrid devices with 1 and 2 layers of GO. In our simulations, we assumed that the GO films were isotropic with the same values of k (i.e., k_{TE} in Fig. 3(b)) for both TE and TM polarizations. As a result, the simulated *PDL* values represent the polarization selectivity caused by the polarization-dependent mode overlap with GO, and the variation between the simulated and measured *PDL* values characterizes the extra polarization selectivity enabled by the loss anisotropy of 2D GO films. For all different T_R and N , the simulated *PDL*'s exhibited positive values, reflecting that the polarization-dependent GO mode overlap contributes to the overall *PDL*.

In Fig. 3(e-i) and 3(e-ii), we further calculated the fractional contributions to the overall *PDL* from the polarization-dependent mode overlap and the material loss anisotropy (where the sum of these two fractions is equal to 1). For all different T_R and N , over 65% of the polarization selectivity is attributed to the loss anisotropy. This highlights its dominance in enabling the functionality of the optical polarizer. It is also interesting to note that the fractional contribution from the loss anisotropy increases as T_R increases. This is mainly due to the fact there is more significant loss anisotropy for rGO, as we discussed in Fig. 3(c).

Dependence on input power and wavelength

For the experiments in Fig. 2, the *IL* was measured at a low input CW power of $P_{in} = \sim 0$ dBm, to ensure that the GO films were not affected by photothermal reduction induced by the CW light. In Fig. 4, we increase the input CW power P_{in} further to induce photothermal reduction of GO and characterize the changes in the polarization selectivity. Compared to GO reduction caused by heating the entire chip on a hot plate (as we did for the experiments in Fig. 2), using input CW power can trigger localized photothermal reduction of GO in the hybrid waveguides, along with dynamic changes in the GO film properties.

Figure 4(a-i) shows the measured *IL* versus P_{in} for the waveguide with 1 layer of unreduced GO (i.e., we directly measured the *IL* without heating the GO-coated chip on a hot plate, unlike what we did later in Fig. 4(b) and 4(c)). The GO film length in the hybrid waveguide was $L_{GO} = \sim 0.4$ mm, and the wavelength of the input CW light was ~ 1550 nm. We measured the *IL* for both TE and TM polarizations, and the results were recorded only when a steady thermal equilibrium state with stable output power was achieved. We chose an input power range of $P_{in} \leq \sim 25$ dBm because the polymer layers in the self-assembled films cannot withstand input powers beyond this range.

In Fig. 4(a-i), the TE-polarized *IL* remained unchanged at ~ 2 dB when $P_{in} \leq \sim 13$ dBm, indicating that the GO reduction did not occur in this power range. For $P_{in} \geq \sim 13$ dBm, the TE-polarized *IL* increased with P_{in} , and reached ~ 12 dB at $P_{in} = \sim 25$ dBm. This reflects that there was loss increase caused by photothermal reduction of GO at high light powers. We also note that the reduction of GO exhibited reversibility within a power range of ~ 13 dBm $\leq P_{in} \leq \sim 21$ dBm, as indicated by the

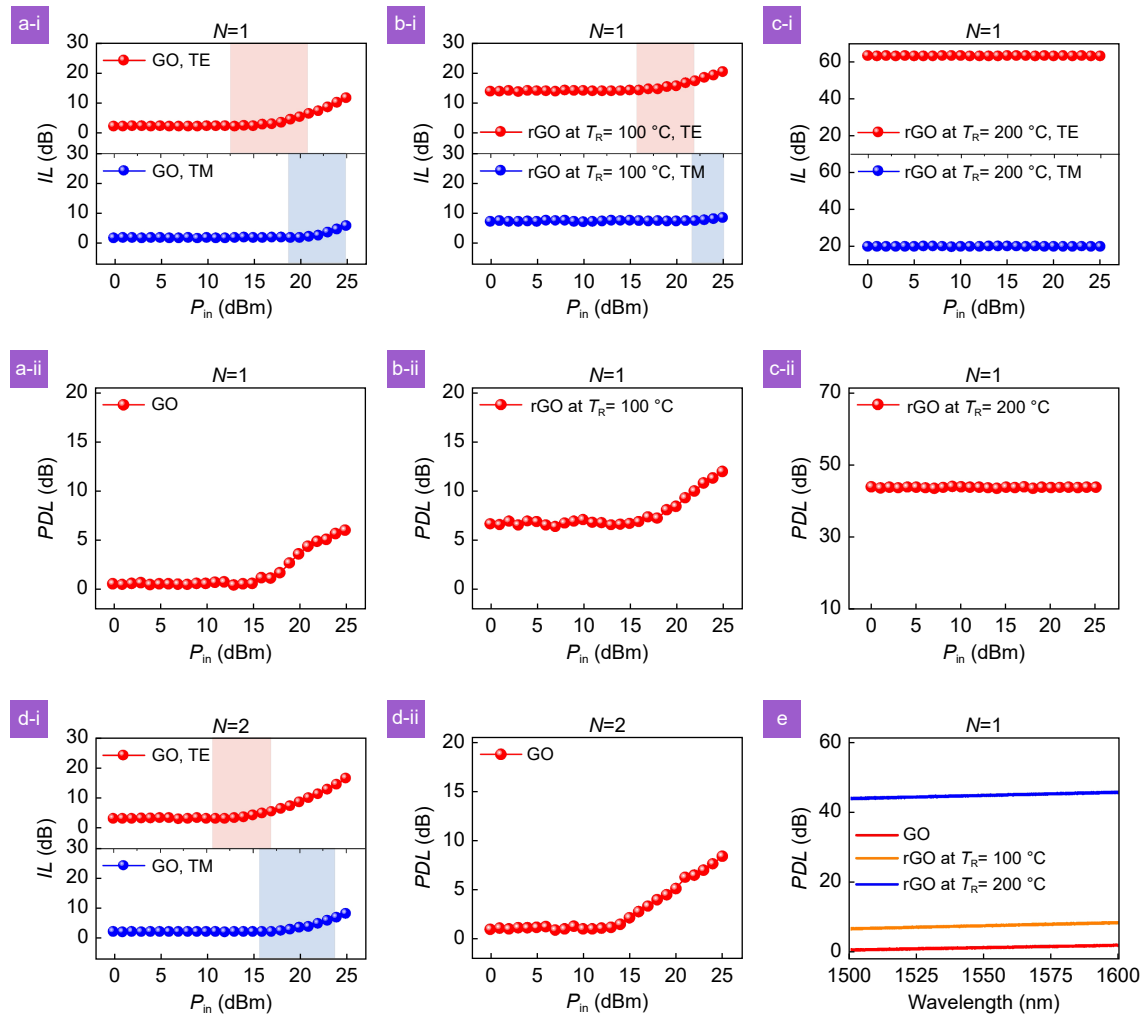


Fig. 4 | (a) Measured (i) TE- and TM-polarized IL and (ii) calculated PDL versus input power (P_{in}) for the hybrid waveguide with 1 layer of GO. (b, c) Measured (i) TE- and TM-polarized IL and (ii) calculated PDL versus P_{in} for the waveguide with 1 layer of rGO after heating at $T_R \approx 100^\circ\text{C}$ and $\sim 200^\circ\text{C}$, respectively. (d) Measured (i) TE- and TM-polarized IL and (ii) calculated PDL versus P_{in} for the waveguide with 2 layers of GO. In (a–d), the red and blue shaded areas in (i) indicate the power ranges associated with reversible GO reduction for TE and TM polarizations, respectively. (e) Measured PDL versus input CW wavelength for the waveguide with 1 layer of un-reduced GO, rGO at $T_R \approx 100^\circ\text{C}$, and rGO at $T_R \approx 200^\circ\text{C}$. In (a–e), the GO film length was ~ 0.4 mm. In (a–d), the input CW wavelength was ~ 1550 nm. In (e), the input CW power was $P_{in} \approx 0$ dBm.

red shaded area. In this power range, after switching off the high-power input and remeasuring the IL with a low input power of $P_{in} \approx 0$ dBm, the IL returned to ~ 2 dB (i.e., the IL for un-reduced GO when $P_{in} \leq \sim 13$ dBm). This reversibility indicates that the photothermally reduced GO was unstable in nature, which reverted to the initial un-reduced status after cooling down in an oxygen-containing ambient. As P_{in} increased beyond ~ 21 dBm, a permanent increase in the IL was observed after turning off the high-power input and remeasuring at $P_{in} \approx 0$ dBm. This reflects that there was permanent reduction of GO induced by the high CW power in this range, where the chemical bonds connecting the carbon network and the OFGs were irreversibly broken, resulting in a lasting

alteration in GO's atomic structure and material properties. The photothermal reduction of GO in GO-Si waveguides is more significant as compared to that observed for GO-silicon nitride and GO-doped silica waveguides^{31,60}, mainly due to the stronger GO mode overlap in the GO-Si waveguides.

In Fig. 4(a-i), the TM-polarized IL increased when $P_{in} \geq \sim 19$ dBm, reaching ~ 6 dB at $P_{in} \approx 25$ dBm. Compared to TE polarization, the power threshold for initiating photothermal reduction of GO was higher for TM polarization. This can be attributed to weaker photothermal effects for TM polarization that result from lower absorption for out-of-plane light waves in the anisotropic 2D GO films. Figure 4(a-ii) shows the

corresponding *PDL* versus P_{in} extracted from Fig. 4(a-i). The *PDL* exhibited no significant changes when $P_{\text{in}} \leq \sim 13$ dBm. However, when P_{in} exceeded ~ 13 dBm, there was an obvious rise in the *PDL* as P_{in} increased. This suggests that increasing the input power improved the polarization selectivity.

Figure 4(b) and 4(c) provide the corresponding results for the hybrid waveguides with 1 layer of rGO after heating at $T_{\text{R}} = \sim 100$ and ~ 200 °C, respectively. For comparison, the GO film length was the same as that of the hybrid waveguide in Fig. 4(a). Prior to measuring the *IL*, the GO-coated chip was heated on a hot plate for 15 minutes, as we did in Fig. 2. According to the results in Fig. 2, the GO films in the hybrid waveguides were reduced after heating at $T_{\text{R}} = \sim 100$ and ~ 200 °C. For rGO at $T_{\text{R}} = \sim 100$ °C in Fig. 4(b), loss increase induced by photothermal reduction was observed for TE polarization when $P_{\text{in}} \geq \sim 16$ dBm. The power threshold of ~ 16 dBm was higher than that for unreduced GO (i.e., ~ 13 dBm in Fig. 4(a)). This indicates that unreduced GO was more susceptible to reduction by the applied CW power, whereas higher power is required to trigger photothermal reduction of rGO.

For rGO at $T_{\text{R}} = \sim 200$ °C in Fig. 4(c), increasing P_{in} did not result in any significant variations in the *IL* and *PDL*. These results further confirm that the photothermal reduction behaviour of GO becomes less obvious as the degree of reduction increases. According to ref.³⁴, rGO exhibits higher thermal conductivity compared unreduced GO, and the thermal conductivity increases with the degree of reduction. The relatively high thermal conductivity of rGO leads to a lower heat accumulation efficiency, which in turn diminishes the photothermal effects and the power-dependent response. In addition to exhibiting a higher anisotropy ratio in Fig. 3(c), rGO shows better thermal stability and stronger immunity to photothermal reduction than GO, making it intriguing for implementing optical polarizers operating at high temperatures and input powers.

Figure 4(d) shows the corresponding results for the waveguide with 2 layers of unreduced GO (i.e., without heating the GO-coated chip on a hot plate). Loss increase induced by photothermal reduction was observed for TE polarization when $P_{\text{in}} \geq \sim 11$ dBm, and reversible GO reduction was observed when ~ 11 dBm $\leq P_{\text{in}} \leq \sim 17$ dBm. Compared to the results in Fig. 4(a), the waveguide with a thicker GO film exhibited a lower power threshold for initiating photothermal reduction and a

smaller power range for reversible reduction. These reflect more significant photo-thermal effects in a thicker GO film.

Figure 4(e) shows the measured *PDL* versus input CW wavelength for the waveguides with 1 layer of GO, rGO at $T_{\text{R}} = \sim 100$ °C, and rGO at $T_{\text{R}} = \sim 200$ °C. For comparison, the input CW power was maintained at $P_{\text{in}} = \sim 0$ dBm. For all three waveguides, the *PDL* exhibited minimal variation (< 1 dB) within the measured wavelength range (from ~ 1500 nm to ~ 1600 nm). This highlights the wide operation bandwidth for the hybrid waveguide polarizers. We also observed a minor increase in the *PDL* with increasing wavelength, mainly due to a slight change in mode overlap with GO caused by dispersion.

Polarization-selective microring resonators

In addition to waveguide polarizers, we also investigate polarization-selective MRRs by integrating 2D GO films onto silicon MRRs. Figure 5(a) shows the schematic of a silicon MRR coated with 1 layer of GO, and a microscopic image of the fabricated device is provided in Fig. 5(b). The silicon MRR had a radius of ~ 20 μm , and the length of the opened windows (i.e., the GO film coating length) was ~ 10 μm . The ring and the bus waveguide in the MRR had the same cross-section of ~ 400 nm $\times$ 220 nm – identical to that for the waveguide polarizers in Fig. 2. The hybrid MRR and the hybrid waveguides in Fig. 2 were fabricated on the same SOI chip via the same processes.

In Fig. 5(c), we compare the TE- and TM- polarized transmission spectra for the hybrid MRRs with 1 layer of GO at different degrees of reduction. All the spectra were measured by scanning the wavelength of an input CW light with a power of $P_{\text{in}} = \sim 10$ dBm (which did not induce any significant photo-thermal effects in the GO films). We first measured the device with unreduced GO in Fig. 5(b) before heating it on a hot plate (the results are labeled as 'initial'). Then, we measured the same device after heating it on a hot plate at different temperatures T_{R} ranging from ~ 50 °C to ~ 200 °C (for 15 minutes, as we did in Fig. 2).

Figure 5(d) shows the extinction ratios (ERs) of the hybrid MRRs extracted from Fig. 5(c). As can be seen, the *ER* of the hybrid MRR after heating at $T_{\text{R}} = \sim 50$ °C showed no obvious difference as compared to that of the unheated MRR. This shows agreement with the results in Fig. 2 and provides further evidence that the reduction of GO did not occur at $T_{\text{R}} = \sim 50$ °C. For $T_{\text{R}} \geq 100$ °C, an increase in the *ER* was observed as T_{R} increased, particularly

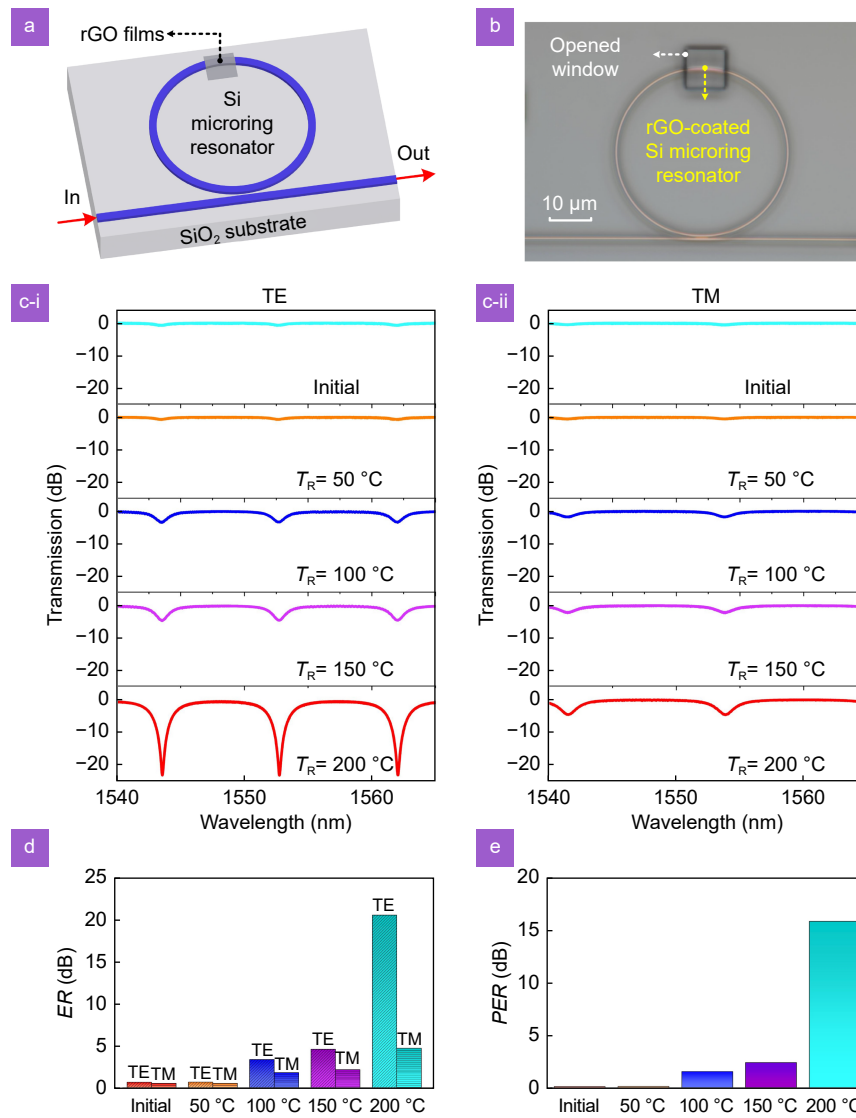


Fig. 5 | (a) Schematic of a silicon microring resonator (MRR) coated with rGO films as an MRR polarizer. (b) Microscopic image of a silicon MRR coated with 1 layer of unreduced GO. (c) Measured (i) TE- and (ii) TM-polarized transmission spectra of the MRR with 1 layer of GO at different degrees of reduction. The same hybrid MRR underwent heating at temperatures T_R ranging from ~ 50 to 200 °C prior to the measurement. The corresponding results measured at room temperature before heating (initial) are also shown for comparison. (d) Extinction ratios (ERs) of the MRRs extracted from (c). (e) Polarization extinction ratios (PERs) extracted from (d). In (c–e), the CW input power was $P_{in} = \sim 10$ dBm.

for TE polarization. This was because the uncoated silicon MRR we chose was over-coupled^{61,62}. As T_R increased, the degree of reduction for GO also increased, leading to higher loss of the GO film. As the loss induced by GO increased, the difference between the round-trip loss and the coupling strength in the hybrid MRR became smaller, resulting in a higher ER (i.e., more approaching the critical coupling condition⁶³).

Figure 5(e) shows the PER obtained by calculating the difference between the TE- and TM-polarized ERs in Fig. 5(d). As shown, the hybrid MRR with unreduced GO exhibited a low polarization selectivity, with a PER of less

than ~ 1 dB. In contrast, The PER increased with T_R when $T_R \geq 100$ °C. After heating at $T_R = \sim 200$ °C, the hybrid MRR exhibited a high PER of ~ 16 dB, highlighting its excellent polarization selectivity.

In Fig. 6, we characterize the power-dependent response for the MRR polarizers in Fig. 5 by increasing the input CW power to induce photothermal reduction of GO. In Fig. 5, we measured the MRRs' transmission spectra by using a single CW input with a low power of $P_{in} = \sim 10$ dBm. In Fig. 6, we employed two CW inputs in our measurements. The first one with a power of P_p was employed as a pump injecting into one of the MRR's

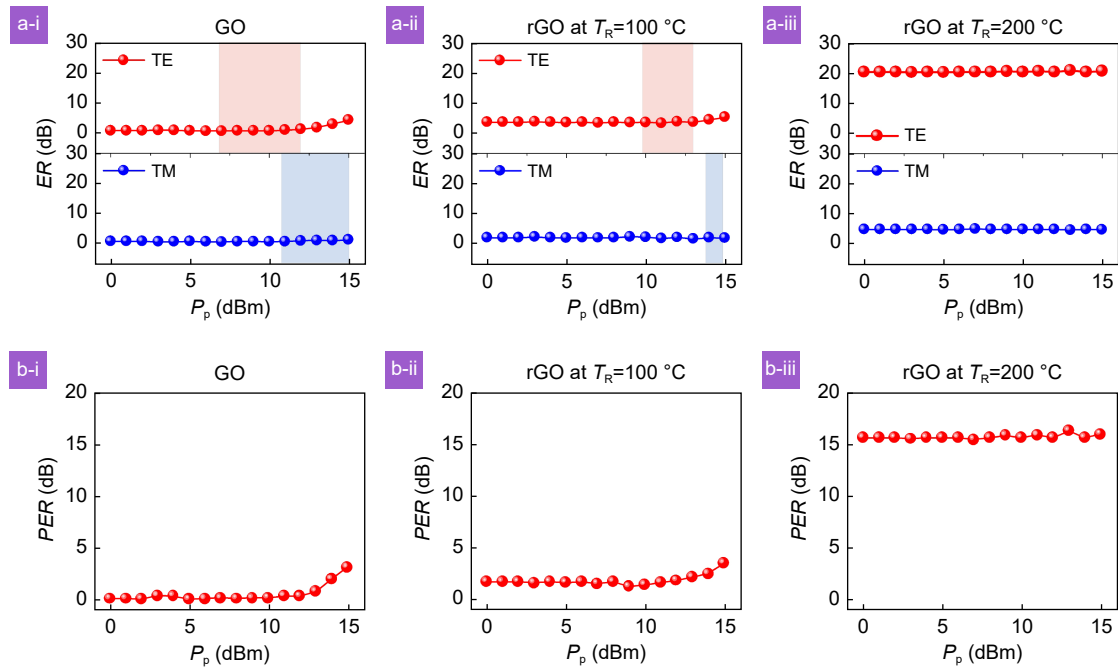


Fig. 6 | (a) Measured TE- and TM-polarized ER versus input CW pump power P_p for the hybrid MRR with 1 layer of GO at different degrees of reduction. (i–iii) Show the results measured for the same hybrid MRR with 1 layer of GO, rGO after heating at $T_R \approx 100^\circ\text{C}$, and rGO after heating at $\sim 200^\circ\text{C}$, respectively. **(b)** PER 's extracted from (a). In (a, b), the red and blue shaded areas indicate the power ranges associated with reversible GO reduction for TE and TM polarizations, respectively.

resonances near $\sim 1550\text{ nm}$. The wavelength of this input CW light was slightly tuned around the resonance until a steady thermal equilibrium state with stable output power was achieved. After this, the second CW light, with a power of $\sim 10\text{ dBm}$ (i.e., the same as that used in Fig. 5), was employed as a low-power probe to scan the MRR's transmission spectrum. Compared to directly using a high-power CW light to scan the spectrum, this approach would not induce significant asymmetry in the measured resonance spectral lineshape caused by optical bistability^{64,65}, thus allowing for a higher accuracy in characterizing the MRR's extinction ratio. In our measurements, the CW pump power P_p was $\leq \sim 15\text{ dBm}$ to prevent damages to the polymer layers in the self-assembled films. We also chose $P_p \geq \sim 0\text{ dBm}$ to ensure that the power of the probe light remained negligible compared to P_p .

In Fig. 6(a), we plot TE- and TM-polarized ER versus input CW pump power P_p . We first measured a hybrid MRR with unreduced GO. As shown in Fig. 6(a-i), the TE-polarized ER exhibited no significant variations when $P_p \leq \sim 7\text{ dBm}$. When $P_p \geq \sim 7\text{ dBm}$, it increased with P_p , indicating that there was increased loss induced by localized photothermal reduction of GO. The power threshold of $\sim 7\text{ dBm}$ for the hybrid MRR was much lower than

that for a comparable hybrid waveguide (i.e., $\sim 13\text{ dBm}$ in Fig. 4(a)), reflecting more significant photothermal effects enabled by the resonance enhancement effect in the hybrid MRR. Compared to TE polarization, a higher power threshold of $\sim 11\text{ dBm}$ was observed for TM polarization, further indicating the anisotropy of 2D GO film. For both polarizations, reversible GO reduction behaviour was also observed within certain power ranges similar to the results in Fig. 4(a).

Figure 6(a-ii) and 6(a-iii) provide the corresponding results for the MRR with 1 layer of rGO after heating at $T_R \approx 100^\circ\text{C}$ and $\sim 200^\circ\text{C}$, respectively. For the device with rGO at $T_R \approx 100^\circ\text{C}$, the increase in ER caused by localized photothermal reduction of GO was observed when $P_p \geq \sim 10\text{ dBm}$ for TE polarization and $P_p \geq \sim 14\text{ dBm}$ for TM polarization. These power thresholds are higher than those in Fig. 6(a-i) for the device with unreduced GO, further confirming that a higher CW power is needed to induce photothermal reduction of rGO. For the device with rGO at $T_R \approx 200^\circ\text{C}$, no significant variations in the ER were observed for both polarizations within the measured input pump power range. This highlights that the highly reduced GO exhibited even less noticeable photothermal reduction behaviour, showing agreement with the results in Fig. 4(c).

Figure 6(b) shows the *PER* calculated from Fig. 6(a). In Fig. 6(b-i), the hybrid MRR with unreduced GO exhibited a low *PER* $< \sim 1$ dB when $P_p < \sim 7$ dBm, and the *PER* increased when $P_p \geq \sim 7$ dBm, reaching ~ 3 dB at $P_{in} = \sim 15$ dBm. For the hybrid MRR with rGO at $T_R = \sim 100$ °C, the *PER* increased from ~ 2 dB in the low-power state without photothermal reduction to ~ 4 dB at $P_p = \sim 15$ dBm. For rGO at $T_R = \sim 200$ °C, the *PER* remained unchanged at ~ 16 dB as P_p increased from ~ 0 dBm to ~ 15 dBm. These results further confirm that the hybrid MRR with highly reduced GO is less susceptible to variations in the input power and shows a better power stability.

In Fig. 6, the variations in the *ER* of the hybrid MRRs cannot directly indicate changes in the properties of the GO films. To address this, we further extracted the extinction coefficients (k) of GO by fitting the results in Fig. 6(a) with theory and plotted them in Fig. 7(a). In our fitting process, we first obtained the GO-induced *EPL* by fitting the measured transmission spectrum of the hybrid MRR based on the scattering matrix method⁶⁶. After that, the k of 2D GO film was extracted from the obtained *EPL* by using the same method as we used in Fig. 3(b). Note that the photothermal changes in GO films coated on integrated waveguides or MRRs actually exhibit nonuniform behavior along the direction of light

propagation³³. This occurs because, as the light power diminishes along the 2D film, the photothermal effects become weaker, resulting in less obvious difference in properties between the photothermally reduced GO and the unreduced GO. For simplification, in our fitting process we regarded the 10- μ m-long GO or rGO films in the hybrid MRRs as uniform films with consistent loss. In principle, such approximation can result in slight deviations in the fit k values, particularly at a high P_p . Despite this, the fit k can still be regarded as an average value reflecting the overall loss performance of the GO films at different P_p .

For unreduced GO in Fig. 7(a-i), the k values at low pump powers (e.g., $P_p = \sim 0$ dBm) are ~ 0.0088 and ~ 0.0017 for TE and TM polarizations, respectively. These values obtained from the MRR measurement show good agreement with those obtained from the waveguide measurement in Fig. 3(b), reflecting the consistency of our GO film fabrication process. The k for TE polarization increases when $P_p \geq \sim 7$ dBm and reaches ~ 0.1634 at $P_{in} = \sim 15$ dBm – ~ 17 times of the k at $P_p < \sim 7$ dBm. This suggests that the change in k induced by localized photothermal reduction of GO is quite significant, even though the variation in *ER* shown in Fig. 6(a) is not very noticeable. This is mainly due to the fact the *ER* in Fig. 6(a) was plotted on a dB scale, which results in less

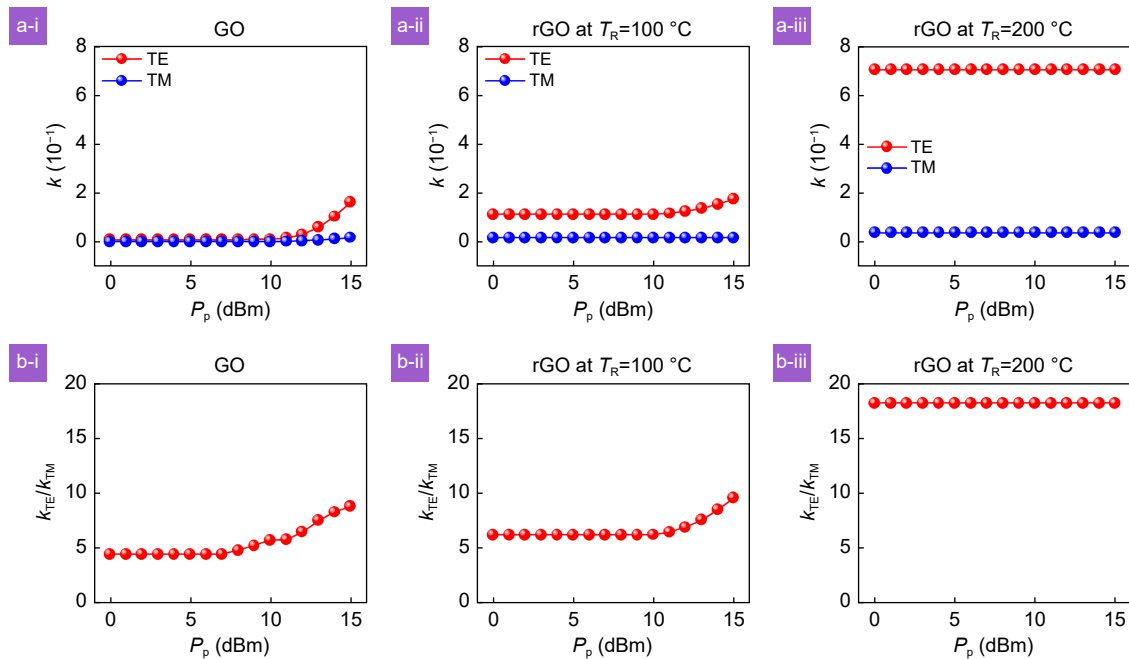


Fig. 7 | (a) Extinction coefficients (k 's) of GO versus P_p obtained by fitting the results in Fig. 6(a) with optical mode simulations. (i – iii) show the results for GO, rGO after heating at $T_R = \sim 100$ °C, and rGO after heating at ~ 200 °C, respectively. **(b)** Anisotropy ratios of k values for TE and TM polarizations (k_{TE} / k_{TM}) extracted from (a).

significant change for the *ER* with a lower value.

Figure 7(a-ii) and 7(a-iii) show the corresponding results for the hybrid MRR with 1 layer of rGO after heating at $T_R = \sim 100^\circ\text{C}$ and $\sim 200^\circ\text{C}$, respectively. For rGO at $T_R = \sim 100^\circ\text{C}$, the TE-polarized k increases from ~ 0.1013 at $P_p < \sim 10$ dBm to ~ 0.1670 at $P_p = \sim 15$ dBm. Whereas the k for TM polarization slightly increases from ~ 0.0183 at $P_p < \sim 15$ dBm to ~ 0.0197 at $P_p = \sim 15$ dBm. In contrast, the k of rGO at $T_R = \sim 200^\circ\text{C}$ remains constant for both polarizations (i.e., $k = \sim 0.7022$ for TE polarization and $k = \sim 0.0367$ for TM polarization) as P_{in} increases from ~ 0 dBm to ~ 15 dBm.

Figure 7(b) plots the anisotropy ratios calculated from Fig. 7(a). In Fig. 7(b-i), the anisotropy ratio for unreduced GO remains constant at ~ 4.5 when $P_p < 7$ dBm, showing agreement with the results in Fig. 3(c). For $P_p \geq 7$ dBm, the anisotropy ratio increases with P_p , achieving a maximum value of ~ 8.8 at $P_{in} = \sim 15$ dBm. For rGO at $T_R = \sim 100^\circ\text{C}$, the anisotropy ratio remains unchanged at ~ 6.2 when $P_p < \sim 10$ dBm before experiencing a gradual increase to ~ 9.6 at $P_p = \sim 15$ dBm. For rGO at $T_R = \sim 200^\circ\text{C}$, the anisotropy ratio remains unchanged at ~ 18.1 within the measured input pump power range. These results further confirm that 2D GO films exhibit more significant loss anisotropy as the degree of reduction increases.

In Table 1, we summarize various waveguide optical polarizers incorporating 2D materials and compare their performance. Here we compare the key performance parameters including *PER*, operation bandwidth (*OBW*), and *IL*, and only show the results for experimental

works. Among the polarizers in Table 1, our work in this paper represents the first experimental demonstration of incorporating rGO into integrated photonic devices to realize optical polarizers. Our experimental results provide evidence for the superiority of rGO in implementing high-performance optical polarizers as compared to other 2D materials. For instance, rGO shows more significant loss anisotropy and better thermal stability compared to GO, which contribute to improved polarization selectivity and power durability. In addition, GO offers advantages for large-scale on-chip integration due to its facile solution-based synthesis processes and transfer-free film coating^{46,70}, and hybrid integrated devices with rGO can be readily fabricated by further reducing GO within the hybrid devices via various reduction methods^{35,71}. This highlights the benefits of rGO polarizers in simplifying device fabrication and their potential for massive manufacturing.

With high polarization selectivity and compact device footprint, integrated optical polarizers with 2D rGO films are anticipated to find potential applications in optical communication and sensing systems, particularly those requiring wide operation bandwidths. The bandwidth of the loss anisotropy of 2D rGO films is remarkably broad, spanning several thousand nanometers and extending from visible to infrared wavelengths³², far exceeding the range demonstrated in Fig. 4(e). This represents a significant advantage that is difficult to achieve with optical polarizers based on bulk materials, where the optical bandwidths are typically restricted to less than 100 nm ^{11,72}. In optical communication systems, the

Table 1 | Comparison of waveguide optical polarizers incorporating 2D materials. *PDL* polarization dependent loss, *OBW* operational bandwidth, *IL* insertion loss.

2D material	Waveguide material	2D material thickness	<i>PDL</i> (dB)	<i>OBW</i> (μm)	<i>IL</i> (dB)	Ref.
Graphene	Polymer	— ^a	~ 19	— ^a	~ 26.0	ref. ⁶⁷
Graphene	Glass	— ^a	~ 27	$\sim 1.23\text{--}1.61$	~ 9.0	ref. ⁶⁸
Graphene	Chalcogenide	Monolayer	~ 23	$\sim 0.94\text{--}1.60$	~ 0.8	ref. ¹⁵
Graphene	Polymer	$> \text{ or } < 10\text{ nm}$ ^b	~ 6	— ^a	~ 9.0	ref. ²²
MoS ₂	Nd:YAG	$\sim 6.5\text{ nm}$	~ 3	— ^a	~ 0.4	ref. ²⁸
MoS ₂	Polymer	$\sim 2.5\text{ nm}$	~ 12.6	$\sim 0.65\text{--}0.98$	< 10	ref. ⁶⁹
MoSe ₂	Polymer	$\sim 24000\text{ nm}$	~ 14	$\sim 0.98\text{--}1.55$	— ^a	ref. ²⁹
GO	Polymer	$\sim 2000\text{ nm}$	~ 40	$\sim 1.53\text{--}1.63$	~ 6.5	ref. ²⁶
GO	Doped silica	$\sim 2\text{--}200\text{ nm}$	~ 54	$\sim 0.63\text{--}1.60$	~ 7.5	ref. ²⁴
GO	Silicon	$\sim 10\text{ nm}$	~ 17	$\sim 1.50\text{--}1.60$	~ 10.3	ref. ²⁵
rGO	Silicon	Monolayer	~ 47	$\sim 1.50\text{--}1.60$	~ 15.7	This work

^aThere is no reported value for this parameter in the literature.

^bThe polymer waveguides with a few-layer graphene film ($< 10\text{ nm}$) and a thicker graphene film ($> 10\text{ nm}$) worked as TM- and TE-pass optical polarizers, respectively.

rGO integrated optical polarizers can be used for reducing polarization-mode dispersion and realizing polarization-division multiplexing^{73,74}. For optical sensing applications such as navigation, astronomical detection, and atmosphere detection, the rGO integrated optical polarizers can enhance sensitivity and accuracy by selecting the desired polarization state of input light. Finally, rGO with high loss anisotropy, broadband response, and high thermal stability can also be employed for implementing other polarization-sensitive optical devices, such as converters, waveplates, beam splitters, and polarization switches¹⁴, which will be the subject of our future work.

Conclusions

In summary, we experimentally demonstrate integrated waveguide and MRR polarizers incorporating rGO. We integrate 2D GO films onto silicon photonic devices with precise control over their thicknesses and sizes, and use two methods – uniform thermal reduction and localized photothermal reduction – to reduce the GO films. Detailed measurements are performed for devices with different lengths, thicknesses, and reduction levels of the GO films. The results show that the devices with rGO exhibit better polarizer performance than those with GO. A maximum *PDL* of ~47 dB is achieved for the hybrid waveguide with rGO, and the hybrid MRR with rGO achieves a maximum *PER* of ~16. By fitting the experimental results with theory, it reveals that rGO exhibits more significant loss anisotropy, with an anisotropy ratio more than 4 times that of GO. In addition, rGO also exhibits enhanced thermal stability and lower sensitivity to photothermal reduction. Our work opens up new opportunities for implementing high-performance polarization-selective devices through on-chip integration of 2D rGO films.

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Author contributions

JY Wu conceived of the idea and designed the research. JY Wu, YN Zhang, and YY Yang designed and fabricated the silicon photonic devices. WB Liu performed the GO synthesis and film coating. JK Hu, D Jin, and LN Jia performed material characterization. JK Hu performed loss measurements, data processing, and theoretical simulations. JK Hu prepared figures of the manuscript. JY Wu, JK Hu, and DJ Moss prepared the text of the manuscript. JY Wu, BH Jia, and DJ Moss jointly supervised the project. D Huang, YJ Wang, BH Jia, and DJ Moss provided funding support. All authors participated in the review and discussion of the manuscript.

Competing interests

Baohua Jia serves as an Editor for the Journal, no other author has reported any competing interests.



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