Photo-thermal tuning of graphene oxide coated integrated optical waveguides

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ABSTRACT

The power-sensitive photo-thermal tuning (PTT) of two-dimensional (2D) graphene oxide (GO) integrated on the top surface of silicon nitride (SiN) waveguides is experimentally investigated. For SiN waveguide coating with monolayer GO, the light power thresholds for reversible and permanent GO reduction are measured. There are three reduction stages identified based on the presence of reversible versus permanent reduction. We also compared the PTT induced by a continuous-wave laser and a pulsed laser with the same average power, confirming that the PTT is primarily determined by the average input power.

Keywords: 2D materials, integrated optics, photo-thermal changes, graphene oxide

1. INTRODUCTION

Graphene oxide (GO) is a two-dimensional (2D) layered material with many appealing properties, including high optical nonlinearity\textsuperscript{1,3}, strong material anisotropy\textsuperscript{4,6}, broadband light absorption\textsuperscript{7,9}, and tunable material properties in wide ranges\textsuperscript{10,12}. Various applications such as light absorbers\textsuperscript{7,8,13}, optical lenses and imaging devices\textsuperscript{14-16}, polarization-selective devices\textsuperscript{5,6}, and nonlinear optical devices\textsuperscript{17-21} have been demonstrated using integrated photonic devices incorporating GO films. GO can be converted to a reduced form with graphene-like properties under strong light irradiation, high temperature, or microwave treatment\textsuperscript{22-26}. Given the difference between the material properties of GO and reduced GO (rGO)\textsuperscript{1,14,27}, it is critical to investigate the mechanisms and conditions for GO reduction in hybrid integrated photonic devices before applying this functional 2D material to integrated photonic devices\textsuperscript{28,29}.

In this paper, we provide a detailed characterization of such changes in GO layers caused by a variety of effects such as photo-thermal reduction, thermal dissipation, and self-heating. We experimentally investigate the photo-thermal tuning (PTT) of 2D GO films coated on integrated optical waveguides, measure the light power thresholds for reversible and permanent GO reduction in silicon nitride (SiN) waveguides integrated with monolayer GO film, and identify three reduction stages based on whether the changes are reversible or permanent. We also compare the PTT induced by a continuous-wave (CW) laser and a pulsed laser with the same average power and observe negligible difference between them. This confirms that the PTT mainly depends on the average power rather than the peak power of input light. These results reveal interesting features for the reduction of GO induced by photo-thermal changes, which are useful for controlling and engineering GO's material properties in hybrid integrated photonic devices.

2. METHODOLOGY

A GO-coated SiN waveguide with a monolayer GO film is depicted schematically in Figure 1a. The cross-section of the bare SiN waveguide is 1.70 × 0.72 μm. A window near the waveguide input allowed relatively high optical power to be
injected into the GO coated segment\textsuperscript{30}. The length of the opened window was $L_w = 1.4$ mm, and the total length of the SiN waveguide was $L = 2$ cm. A solution-based method (first proposed in Ref. \textsuperscript{14}) that enabled transfer-free and layer-by-layer film coating was used to coat 2D layered GO films onto the SiN waveguide. This GO coating method is highly scalable, enabling the precise control of the GO layer number (i.e., film thickness), the ability to coat large-area films, and good film attachment onto integrated chips\textsuperscript{14,29,31}. A detailed characterization of the thicknesses (i.e., layer numbers) of the as-prepared GO films was reported in Ref. \textsuperscript{5,14,17,18,32} using atomic force microscopy (AFM). A micrograph of the fabricated device corresponding to Figure 1a is shown in Figure 1b. The GO film coated on the chip surface had good morphology, high transmittance, and high uniformity. Figure 1c depicts a schematic for the cross section of the GO-SiN waveguide in Figure 1a, while Figure 1d depicts the corresponding TE mode profile. The light-matter interaction between the waveguide evanescent field and the GO film can cause power-sensitive photo-thermal changes in the GO film, as previously observed\textsuperscript{17,28,32}.

![Figure 1. (a) Schematic illustration of a SiN waveguide coated with 1 layer of GO. (b) A micrograph showing the area around the opened window of the fabricated device corresponding to (a). (c) Schematic illustration of the cross-section of the hybrid waveguide. (d) TE mode profile corresponding to (c).](image)

3. RESULTS

Figure 2a shows the measured insertion loss of the integrated waveguide coated with one layer of GO versus the input CW power. Unless otherwise specified, the input power of CW light or optical pulses in this paper represents the power coupled into the waveguide after subtracting the fiber-to-chip coupling loss. To characterize both reversible and permanent changes in material properties, we turned off the high-power CW light after each measurement and remeasured the insertion loss with low-power CW light at 0 dBm. The results measured using the high-power and the low-power CW light sources are shown by the red and blue dots, respectively. As can be seen, the evolution of the PTT of the GO film can be divided into three reduction stages. At Stage I, when the input power was below 20 dBm, the insertion loss of the waveguide remained constant despite the increase in input power, indicating that there was negligible change in the absorption of the GO film and that the light power was not high enough to induce obvious photo-thermal changes. At Stage II starting from 20 dBm, the insertion loss showed a slight but observable increase with the input power, indicating the occurrence of the photo-thermal changes in the GO film. The results measured using low-power CW light after turning off the high-power CW light remained constant. This reflects the fact that there were no permanent changes in the GO films, and the photo-thermal changes at this stage were reversible. These features of the photo-thermal changes in the GO films are consistent with previous reports\textsuperscript{17,28,30,33}. For Stage III, when the input power was further increased to above 22 dBm, the results measured using low-power CW light also showed an obvious increase with input power. In addition, the difference between the red dots and their corresponding blue dots indicates that there was still reversibly reduced GO and only part of the GO film was permanently reduced. We infer that there would be a new stage after Stage III at even higher powers, where the difference between the red and blue dots at the same power would vanish due to the full reduction of all the GO films\textsuperscript{34,35}. We could not observe this stage in our experiments since we had already applied the maximum experimentally available power to the DUT.

Figure 2b depicts the GO-induced excess propagation loss (EPL) extracted from Figure 2a. The $EPL$ (dB/cm) is defined as

$$EPL = (IL - IL_0)/L_w$$

(1)

where $IL$ is the measured insertion loss of the hybrid waveguide in Figure 2a, $IL_0$ is the insertion loss of the bare waveguide, and $L_w$ is the GO film length.
To compare the PTT induced by CW light versus optical pulses, we measured the EPLs of hybrid waveguides with a single GO layer for both CW light and optical pulses with the same average power. The results are shown in Figure 3. The optical pulses had a repetition rate of ~60 MHz and a pulse width of ~3.7 ps, which corresponded to a peak power $4 \times 10^3$ times higher than the CW light with the same average power. As can be seen, both the CW light and the optical pulses induced measurable EPLs at high average input powers. The small difference between them indicates that the EPL was mainly a function of the average power rather than peak power. This agrees with observations in GO films arising from photo-thermal processes in previous works\cite{17,28,32}, and further confirms the existence of the photo thermal changes. In contrast, the changes induced by ultrafast nonlinear optical processes such as four-wave mixing, two-photon absorption, and saturable absorption are dependent on the peak input light power\cite{30,36-40}. The slightly lower EPL induced by optical pulses compared to CW light can be attributed to saturable absorption in the GO films caused by the high peak powers, which was also observed in previous works\cite{18,21,41}. We also measured permanent EPLs at low-power CW light (0 dBm) after turning off the high-power CW light and optical pulses. The permanent EPLs induced by the CW and optical pulses showed negligible difference, reflecting the fact that the permanent reduction of GO was mainly induced by the photo-thermal changes.

Figure 3. Experimental results of the total and permanent EPL induced by a CW light and optical pulses versus average input power for the hybrid waveguides coated with 1 layer of GO.

4. CONCLUSIONS

We present detailed investigations of the PTT of GO films coated on integrated optical waveguides. Reversible and permanent GO reduction is observed by applying different CW laser powers to the devices with one and two layers of
GO. The corresponding power thresholds are measured, with three reduction stages being identified. For the device with one layer of GO, the power threshold for reversible and permanent GO reduction are ~20 and ~22 dBm, respectively. The photo-thermal changes induced by CW light and optical pulses with the same average power are also compared, which show negligible difference and confirms that the PTT mainly depends on the average input power. These results are useful for controlling and engineering the material properties of GO in hybrid integrated photonic devices.

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