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Research Article

Graphene oxide-based waveguides for enhanced self-phase modulation

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Abstract

The enhanced self-phase modulation (SPM) in silicon nitride (Si_3N_4) and silicon (Si) waveguides integrated with graphene oxide (GO) films is experimentally demonstrated. By using both picosecond and femtosecond optical pulses, we observe significant spectral broadening in the waveguides due to the high Kerr nonlinearity of GO films. The maximum broadening factors of up to ~3.4 and ~4.3 are achieved in GO-coated Si_3N_4 waveguides and GO-coated Si waveguides, respectively. The spectral broadening for femtosecond pulses is more significant than the picosecond pulses, which can be attributed to their relatively high peak power. These results show the strong potential of GO films for improving the Kerr nonlinearity of photonic devices.

Introduction

Self-Phase Modulation (SPM) is one of the most important third-order nonlinear optical processes that occur in a nonlinear medium [1-3], which has been widely used in many applications, such as optical spectroscopy [4,5], optical logic gates [6,7], optical diodes [8,9] and optical coherence tomography [10,11].

The on-chip integrated photonic devices based on SPM will reap attractive benefits of compact footprint, high stability, high scalability, low power consumption, and low-cost mass production [12-15]. Although silicon (Si) has been a leading device platform for integrated photonics [16-18], its strong two-photon absorption (TPA) at near-infrared wavelengths results in a low nonlinear figure-of-merit (FOM), which significantly hinders the improvement of SPM performance in Si devices at the telecom band. To address this, other complementary metal-oxide-semiconductor (CMOS) compatible integrated platforms such as silicon nitride (Si_3N_4) and high-index doped silica glass (Hydex) have been utilized for nonlinear optics owing to their low TPA in this wavelength range.

To overcome the limitations of these existing platforms and improve their nonlinear optical performance, the on-chip integration of two-dimensional (2D) materials with ultrahigh Kerr nonlinearity has been proposed [19-22]. Amongst the different 2D materials, GO has shown many advantages due to its distinct optical properties, including a high Kerr nonlinearity, relatively low loss, facile synthesis processes, and high compatibility with CMOS fabrication.

Here, the enhanced SPM in Si_3N_4 and Si waveguides integrated with GO films by using both picosecond and femtosecond optical pulses is experimentally reported. Owing to the high Kerr nonlinearity of GO, the hybrid waveguides show significantly improved spectral broadening compared to the uncoated waveguide, achieving the maximum broadening factor (BF) of up to ~3.4 [23] and ~4.3 [24] for the hybrid Si_3N_4 and Si waveguides, respectively. These results verify the effectiveness of on-chip integrating 2D GO films to improve the SPM performance of photonic devices.

Device fabrication and characterization

Figure 1 (a-i) shows a schematic cross-section of the GO-coated Si_3N_4 waveguide and Figure 1 (a-ii) shows the

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corresponding transverse electric (TE) mode profile [23]. The interaction between light and the GO film possessing an ultrahigh Kerr nonlinearity can be excited by the waveguide evanescent field, which underpins the enhancement of the SPM response in the hybrid waveguide. Figure 1(a-iii) shows a microscope image of a Si_3N_4 integrated chip uniformly coated with a monolayer GO film, where the coated GO film exhibits good morphology, high transmittance, and high uniformity. Figure 1(b) shows a schematic cross-section, TE mode profile, and a microscope image of a Si waveguide uniformly coated with a monolayer GO film [24].

SPM experimental measurement and results

We used both picosecond (~1.9 ps & ~3.9 ps) and femtosecond (~180 fs) optical pulses to perform SPM measurements on the GO-coated Si_3N_4 waveguides and SOI nanowires [23-25]. Picosecond and femtosecond optical pulses generated by pulsed fiber lasers were delivered into the hybrid waveguides, with a VOA to tune the input pulse energy. Figures 2(a) and 3(a) show the SPM experimental results for GO-coated Si_3N_4 and Si waveguides with picosecond optical pulses, respectively [23,25]. To compare with the picosecond optical pulses, we also show the results with femtosecond optical pulses in Figures 2(b) and 3(b) [23,24]. In each Figure, (i) shows normalized spectra of optical pulses before and after propagation through the hybrid waveguides with different layers of GO. The output spectra after propagating through the hybrid waveguides show more significant spectral broadening, reflecting the

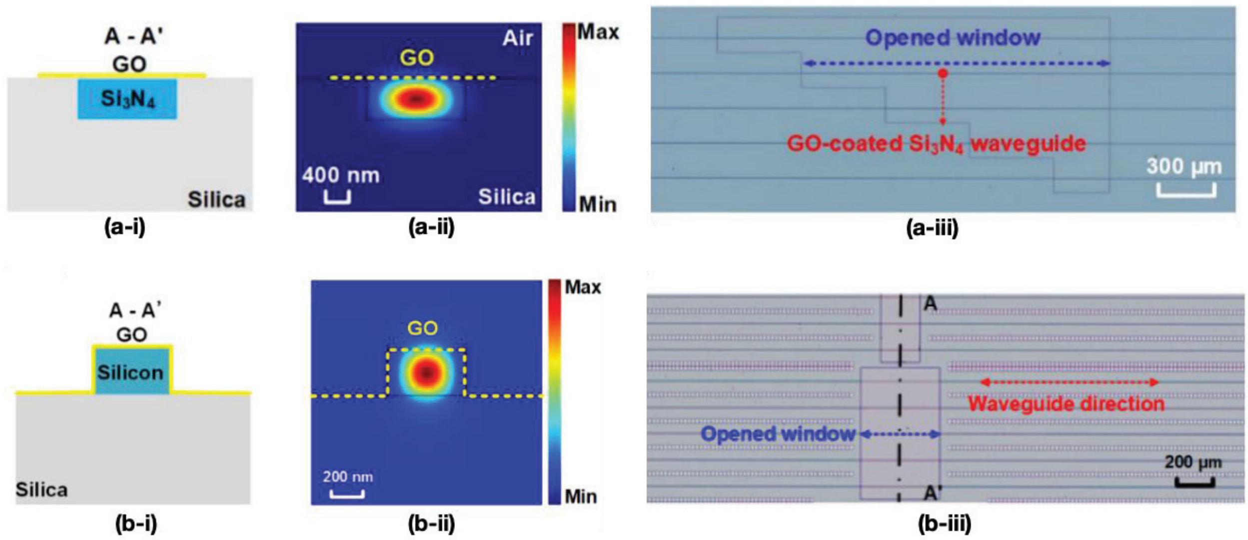

Figure 1: (a) GO-coated Si_3N_4 waveguides (b) GO-coated Si waveguides. (i) Schematic illustration of the cross-section and (ii) the corresponding TE mode profile of the waveguides in (i). (iii) Microscope image of the devices uniformly coated with a monolayer GO film.

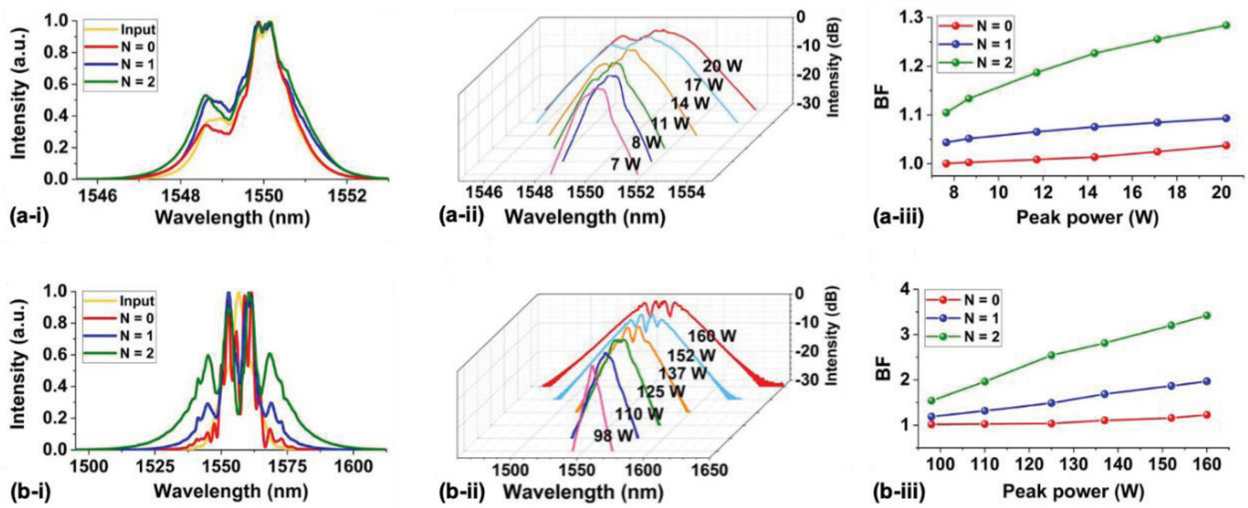

Figure 2: GO-coated Si_3N_4 waveguides (a) SPM experimental results using picosecond optical pulses. (b) SPM experimental results using femtosecond optical pulses. (i) Normalized spectra of optical pulses before and after propagation through the hybrid waveguides with 1 and 2 layers of GO at an input peak power of ~20 W in (a) and ~160 W in (b). (ii) Optical spectra measured at different input peak powers for the hybrid waveguides with 2 layers of GO. (c) BFs of the measured output spectra versus input peak power for the hybrid waveguides with 1 and 2 layers of GO. In (i) and (iii), the corresponding results for the bare Si_3N_4 waveguides are also shown for comparison.

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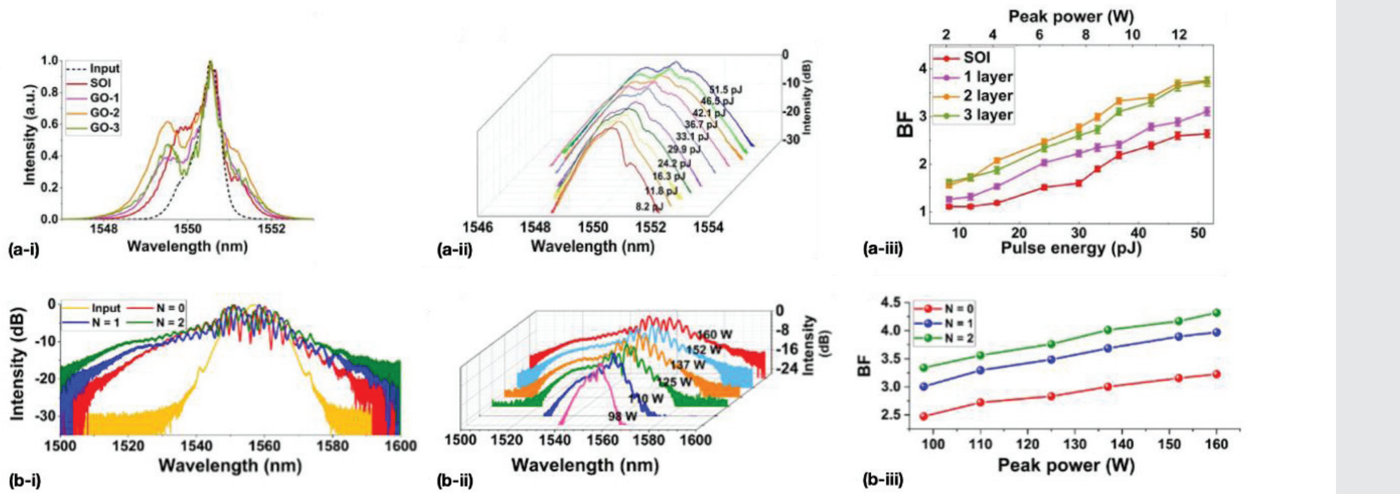

Figure 3: GO-coated Si waveguides (a) SPM experimental results using picosecond optical pulses. (b) SPM experimental results using femtosecond optical pulses. (i) Normalized spectra of optical pulses before and after propagation through the hybrid waveguides with different layers of GO at an input peak power of ~13 W in (a) and ~160 W in (b). (ii) Optical spectra measured at different input peak powers for the hybrid waveguides with 2 layers of GO. (c) BFs of the measured output spectra versus input peak power for the hybrid waveguides with different layers of GO. In (i) and (iii), the corresponding results for the bare Si waveguides are also shown for comparison.

improved SPM performance in these devices. (ii) shows optical spectra measured at different input peak powers for the hybrid waveguides with 2 layers of GO and (iii) shows BFs of the measured output spectra versus input peak power for the hybrid waveguides with different layers of GO. In (i) and (iii), the corresponding results for the uncoated waveguides are also shown for comparison. As expected, the spectral broadening of the output spectra becomes more significant as the peak power increases. We achieved the maximum BF of up to ~3.4 for the GO-coated Si_3N_4 waveguides and ~4.3 for the GO-coated Si waveguides. Meanwhile, we also observe that the spectral broadening for femtosecond optical pulses is more significant than the picosecond pulses due to their high peak power.

Conclusion

An enhanced SPM-induced spectral broadening of both picosecond and femtosecond optical pulses after propagation through Si_3N_4 and Si waveguides integrated with 2D GO films is demonstrated. By using a solution-based, transfer-free coating method, we achieve the integration of GO films onto waveguides with precise control of the film thickness. A detailed SPM measurement using the fabricated devices is performed, achieving a maximum BF of ~3.4 and ~4.3 for the Si_3N_4 and Si devices with two layers of GO, respectively. Finally, the results for the picosecond and femtosecond optical pulses are compared. This work verifies the effectiveness of improving the nonlinear performance of CMOS-compatible photonic devices through the integration of 2D GO films.

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