Enhanced Kerr optical nonlinearity in waveguides integrated with 2D layered GO films

Yang Qu^a, Jiayang Wu^a, Yunyi Yang^a, Xingyuan Xu^a, Linnan Jia^a, Yuning Zhang^a, Yao Liang^a, Sai T. Chu^b, Brent E. Little^c, Roberto Morandotti^d, Baohua Jia^a, and David Moss^a

^aCentre for Micro-Photonics, Swinburne University of Technology, Hawthorn, VIC 3122, Australia

^bCity University of Hong Kong, Tat Chee Avenue, Hong Kong, China

^cXi'an Institute of Optics and Precision Mechanics Precision Mechanics of CAS, Xi'an, China

^dINRS –Énergie, Matériaux et Télécommunications, 1650 Boulevard Lionel-Boulet, Varennes, Québec, Canada

ABSTRACT

We experimentally demonstrate enhanced optical Kerr nonlinearity of hybrid integrated waveguides coated with layered graphene oxide (GO) films. Owing to the high Kerr nonlinearity of GO and strong mode overlap between GO and waveguide, up to ~9.5-dB enhancement of four wave mixing (FWM) conversion efficiency is achieved.

1. INTRODUCTION

Nonlinear photonic chips can achieve all-optical signal generation and processing with far superior performance to electronic chips— particularly with respect to speed [1-3]. Although silicon has been the leading platform for nonlinear optics for many years [4-7] and more recently for integrated photonic devices [3, 8-18], its strong two-photon absorption (TPA) at near-infrared wavelengths poses a fundamental limitation to the nonlinear performance of silicon photonic devices in the telecom band [3] despite the fact that TPA can sometimes be of benefit for certain processes [19 - 21]. Benefitting from very low linear and nonlinear losses, high-index doped silica glass has been a successful nonlinear photonic device integration platform [22 - 50]. However, compared to silicon and silicon nitride, the relatively low Kerr nonlinearity of the doped silica glass limits the performance of nonlinear photonic devices made from this platform. This has motivated the search for alternate platforms for nonlinear optics including chalcogenide glass and amorphous silicon [51-62]. However, it is of significant interest to be able to integrate highly nonlinear materials into any platform rather than use the intrinsic nonlinearity of the platform itself [63, 64].

Graphene oxide (GO) has become a rising star of the graphene family due to the ease of preparation and the tunable material properties [65-72]. Previously, we reported a giant Kerr nonlinear response of GO films of 4–5 orders of magnitude higher than that of high-index doped silica glass [1]. In addition, GO has much lower loss and larger bandgap as compared with graphene, which yields low TPA in the telecom band [66-72]. GO also has better large-scale manufacturing capability, critical for the practical implementation of high-performance nonlinear photonic devices.

In this paper, we experimentally demonstrate significantly improved Kerr nonlinearity of high-index doped silica glass waveguides integrating with layered GO films [67]. We demonstrate significantly enhanced four-wave mixing (FWM) efficiency in the GO hybrid integrated waveguides, with a maximum conversion efficiency (CE) enhancement of ~9.5 dB being achieved for a 1.5-cm-long integrated waveguide incorporating 2 layers of GO. We also carried out FWM measurements for different pump powers, wavelength detuning, GO coating lengths, and GO layer numbers. The experimental results confirm the improved Kerr nonlinearity of integrated photonic devices incorporated with GO films. Our results are consistent with nonlinear optics in other photonic platforms integrated with GO layers [64-68].

2. DEVICE FABRICATION AND CHARACTERIZATION

Figure 1(a) shows the GO-coated integrated waveguides made from high-index doped silica glass. The integrated waveguide is surrounded by silica except that the upper cladding is removed (via chemical mechanical polishing) to enable coating the waveguide with GO films. The GO films, with a thickness of about 2 nm per layer, were introduced

Fig. 1. (a) Schematic illustration of hybrid waveguides integrated with GO films. (b) Image of the hybrid integrated waveguide with two layers of GO. (c) Raman spectra of GO on the integrated chip. (d) Measured refractive indices (n) and extinction coefficients (k) of GO and graphene. (e) Measured insertion loss of a 1.5-cm-long integrated waveguide with different numbers of GO layers. (f) Additional propagation loss of the integrated waveguide with different numbers of GO layers.

on top of the integrated waveguide. The Kerr coefficient of GO is on the order of $10^{-15} \sim 10^{-14} \text{ m}^2/\text{W}$ [66-72], slightly lower than that of graphene ($\sim 10^{-13} \text{ m}^2/\text{W}$), but still orders of magnitude higher than that of high-index doped silica glass ($\sim 10^{-19} \text{ m}^2/\text{W}$) and silica ($\sim 10^{-20} \text{ m}^2/\text{W}$) [1]. The waveguides were fabricated via CMOS compatible processes [1]. An image of the integrated waveguide incorporating 2 layers of GO is shown in Fig. 1(b). To couple light into/out of the integrated waveguides, we employed a single-mode fibre (SMF) array for butt coupling. Figure 1(c) depicts the total insertion loss of the integrated waveguides with different numbers of GO layers. The coated GO layers only affected the propagation (not coupling) loss, which is shown in Fig. 1(d) as a function of the number of layers.

3. FWM EXPERIMENTS

The FWM experimental results are shown in Fig. 2. The FWM spectra of the integrated waveguide without GO and with 2 layers of GO are shown in Fig. 2(a). It can be seen that although the hybrid integrated waveguide had additional propagation loss ($\sim 2.6 \text{ dB}$), it clearly shows enhanced idler output powers as compared with the same waveguide without GO. The CE (defined as $P_{\text{out, idler}}/P_{\text{out, signal}}$) of the integrated waveguide with and without GO were $\sim -47.1 \text{ dB}$ and $\sim -56.6 \text{ dB}$, respectively, corresponding to a CE enhancement of $\sim 9.5 \text{ dB}$ and a net CE enhancement of $\sim 6.9 \text{ dB}$. For the integrated waveguide coated with 1 to 5 layers of GO, zoom-in spectra of the generated idlers for the same pump power are shown in Fig. 2(b). The output powers of the idler for various pump powers coupled to the waveguide without GO and with 2 layers of GO are shown in Fig. 2(c). One can see that as the pump power increased, the idler power increased with no obvious saturation for both samples, which reflects the low nonlinear absorption of both the high-index doped silica glass as well as the GO layers in the telecom band. The net CE enhancement for various pump powers is shown in Fig. 2(d). The variation in idler power when the pump wavelength was fixed at 1550 nm and the signal wavelength detuned around 1550 nm is shown in Fig. 2(e). The output powers of idler light for the integrated waveguide coated with different lengths of GO are depicted in Fig. 2(f). This phenomenon reflects the trade-off between FWM enhancement and propagation loss in these hybrid integrated waveguides.

Fig. 2. (a) FWM spectra of the waveguide without GO and with 2 layers of GO. (b) Zoom in spectra of the idlers after FWM in the waveguide with 0–5 layers of GO. (c) Output powers of idler for various pump powers. (d) Net CE enhancements for various pump powers. (e) Power variations of the output idler when the signal wavelength was detuned. (f) Output powers of idler for the waveguide with different coating lengths of GO. The GO coating length in (a)–(e) is $\sim 1.5 \text{ cm}$. The pump power coupled to the waveguide in (a), (b), (e), (f) is $\sim 22 \text{ dBm}$. WG: waveguide.

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