Strongly enhanced four wave mixing in micro-ring resonators integrated with 2D graphene oxide films

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Abstract: Two-dimensional layered graphene oxide films are integrated with micro-ring resonators to experimentally demonstrate enhanced four-wave mixing, achieving up to ~7.6-dB enhancement in conversion efficiency for a uniformly coated device and ~10.3-dB for a patterned device.

1. Introduction

As a fundamental third-order ($\chi^{(3)}$) nonlinear optical process [1], four-wave mixing (FWM has found wide applications in all-optical signal generation and processing, such as wavelength conversion, optical comb generation, quantum entanglement, optical sampling, and many others [2-5]. Integrated micro-ring resonators (MRRs), which confine light in compact micro-scale resonant cavities, are key building blocks for photonic integrated circuits [6-8]. Compared with FWM in waveguides, FWM in MRRs can provide dramatically enhanced conversion efficiencies (CEs) due to resonant enhancement of the optical field, thus significantly reducing the power requirements.

Although silicon has been a leading integrated platform for linear optics, for nonlinear optics it suffers from strong two-photon absorption (TPA) in the telecommunications band, which greatly limits the FWM performance [1]. Other integrated platforms such as silicon nitride and high index doped silica glass, though have a much weaker TPA, still face limitations in terms of FWM efficiency since their Kerr nonlinearity (n_2) is over an order of magnitude smaller than that of silicon [9, 10]. Recently, [11] we demonstrated enhanced FWM in waveguides integrated with two-dimensional (2D) layered graphene oxide (GO) films as well as high performance linear polarizers in waveguides and MRRs [12]. Here, [13] we report enhanced FWM in CMOS-compatible MRRs integrated with GO films. By using a large-area, transfer-free, layer-by-layer GO coating method together with photolithography and lift-off processes, we achieve precise control of the film thickness, placement, and coating length. Owing to the strong light-matter interaction in the MRRs integrated with highly nonlinear GO films, the FWM efficiency in the hybrid MRRs is significantly improved. We achieve up to ~7.6-dB enhancement in the FWM CE for an MRR uniformly coated with 1 layer of GO and ~10.3-dB for a device patterned with 50 layers of GO. These results confirm the high nonlinear optical performance of integrated photonic resonators incorporated with layered GO films.

2. Four-wave mixing in GO-coated MRRs

Figure 1(a) shows microscopic images of an integrated MRR patterned with 50 layers of GO (~50 μm pattern length). The MRR was fabricated on a high index doped silica glass platform using CMOS compatible fabrication processes [11, 12]. Chemical mechanical polishing was used to remove the upper cladding, so as to enable GO film coating on the top surface of the MRR. The coating of layered GO films was achieved via a solution-based method that yields transfer-free [14], layer-by-layer GO film deposition [14]. Based on this GO coating technique, we achieved GO patterning on integrated photonic devices via photolithography and lift-off processes. Figure 1(b) shows a scanning electron microscope image of the 2D layered GO film, with up to 5 layers of GO (with a thickness of ~2.25 nm on

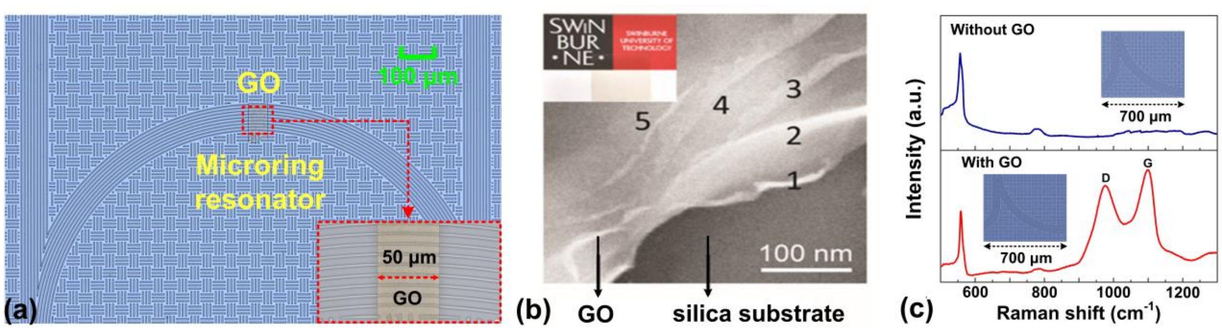

Fig. 1. (a) Microscopic image of an integrated MRR patterned with 50 layers of GO. Inset shows zoom-in view of the patterned GO film. (b) Scanning electron microscope image of 2D layered GO film. (c) Raman spectra of an integrated chip without GO and with 2 layers of GO.

average for each layer). Figure 1(c) shows the measured Raman spectra. The presence of the representative D and G peaks of GO confirms the integration of GO film onto the top surface.

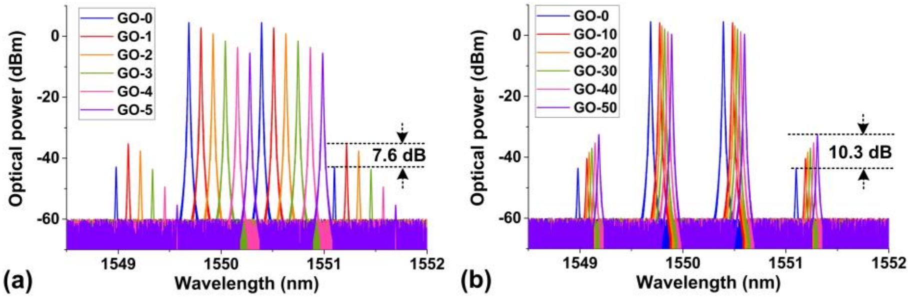

Fig. 2. Optical spectra of FWM at a pump power of 22 dBm for the MRRs with (a) 1−5 layers of uniformly coated and (b) 10−50 layers of patterned GO films, respectively. The results for uncoated MRR (GO-0) are also shown for comparison.

Figure 2(a) shows the FWM spectra of the MRRs uniformly coated with 1−5 layers of GO, together with the FWM spectrum of the uncoated MRR. For comparison, we kept the same pump power of ~22 dBm coupled into the MRRs. As compared with the uncoated MRR, the GO-coated MRRs had an additional insertion loss, while the MRRs with 1 and 2 layers of GO clearly show enhanced idler output powers. The CE of the MRR without GO and with 1 layer of GO were ~-48.4 dB and ~-40.8 dB, respectively, corresponding to a CE enhancement of 7.6 dB for the GO-coated MRR. Figure **2**(b) shows the FWM spectra of the MRRs with 10−50 layers of patterned GO. The GO coating length was ~50 µm and the pump power (22 dBm) was the same as that in Fig. 2(a). The results for all the tested GO layer numbers show enhanced idler output powers. In particular, there is a maximum CE enhancement of ~10.3 dB for the MRR patterned with 50 layers of GO. Figures 3(a)−(c) show the FWM spectra versus Δλ (wavelength spacing between pump and signal) for the uncoated MRR, the uniformly coated MRR with 1 layer of GO, and the patterned MRR with 50 layers of GO, respectively. The measured CE versus Δλ is depicted in Figure 3(d) where we see that, for all three MRRs, the CE only shows a slight decrease with Δλ, reflecting the low dispersion of the doped silica MRR and the GO-coated MRRs, thus enabling effective phase matching for broadband FWM. Compared with other 2D materials, n_2 for GO is lower than graphene but still two orders of magnitude higher than bulk silicon [11-16], which demonstrates the high potential of GO as a new optical material for nonlinear photonic applications. Further, like Si-Ge heterostructures, [17, 18] GO may also offer interesting possibilities for both 2nd and 3rd order nonlinear effects courtesy of its complex anisotropic nonlinear optical characteristics.

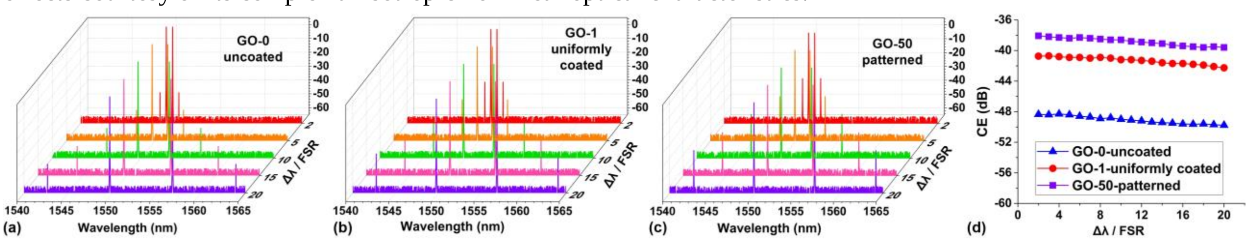

Fig. 3. (a)−(c) Optical spectra of FWM at different resonant wavelengths for the uncoated MRR, the MRR uniformly coated with 1 layer of GO, and the MRR patterned with 50 layers of GO, respectively. Δλ and FSR represent the wavelength spacing between pump and signal and the free spectral ranges of the MRRs, respectively. (d) Measured CE versus Δλ/FSR for the MRRs in (a)−(c). The pump power in (a)−(d) was 22 dBm.

3. Conclusion

We demonstrate enhanced FWM in MRRs integrated with layered GO films. We perform FWM measurements for MRRs uniformly coated and patterned with GO films, achieving up to ~7.6-dB and ~10.3-dB enhancement in the FWM CE for the MRRs uniformly coated with one layer of GO and patterned with 50 layers of GO, respectively.

4. References

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