Selectively formed spot-size converters for efficient coupling in graphene-integrated silicon photonics

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Abstract: We demonstrate an improvement of coupling efficiency between an optical fiber and graphene-integrated silicon photonics circuit. Selectively formed spot-size converters (SSCs) enable low coupling losses of 1.4 and 2.4 dB/facet for TE and TM modes at 1550 nm without damaging for the single-layer graphene. We achieved broadband coupling from 1300 to 1650 nm. The result maximizes the potential of graphene such as its perfect wavelength independence. Finally, we demonstrate the reductions of coupling loss and ripples by integrating the SSCs on a graphene integrated silicon-ring resonator.

1.! Introduction

Silicon- and graphene-integrated optical devices have recently attracted much attention because graphene has extremely high optical absorption, wavelength independence and high optical nonlinearity [1]. The most well-known silicon- and graphene-integrated optical devices are modulators [2], and photodetectors. However, graphene devices have seriously low coupling efficiency due to the difficulty of depositing SiO_2 on graphene, which is easily affected by oxygen plasma and mechanical stress. Air-cladding two-dimensional grating couplers have been applied to avoid these problems, but high coupling loss (about 3-4 dB/facet for TE and TM modes) and strong wavelength dependence (about 60 and 40 nm in TE and TM modes for 3-dB roll off) are still concerns [2,3]. Therefore, the distinctive feature of wavelength independence in graphene is totally counteracted. On the other hand, we have developed an air-cladding edge coupler to obtain a broadband coupling, but the losses were very high (7.5 and 15.5 dB/facet for TE and TM modes) [4], which caused ripples between input and output surfaces. Thus, we need to enhance the coupling efficiency and broaden the 3-dB spectral bandwidth. In this paper, we propose spot-size converters (SSCs) with selectively formed SiO_2 film for graphene-integrated optical-electrical circuits and bio-chemical sensors.

2.! Design and fabrication

Fig. 1 shows a schematic view of an SSC. We selected three tip widths of 150, 200 and 250 nm to investigate the coupling loss with device fabrication. We estimated the coupling loss to be around 1.5-3 dB/facet by simulation. In the fabrication, we formed a silicon waveguide and inversed-taper waveguide with 400 and 150-250 $\times$ 200 nm cores by electron-beam lithography and reactive ion etching on a 4-inch silicon-on-insulator (SOI) wafer. Next, we spin-coated PMMA on single-layer graphene, which had been grown on Cu substrate, and then, after Cu etching, fabricated the graphene pattern on a silicon waveguide. The detailed graphene fabrication process is described in our previous report [4]. Finally, we formed a high-aspect-ratio negative resist on the wafer to avert causing damage to the graphene, and SiO_2 was deposited by electron-cyclotron-resonance chemical-vapor-deposition (ECR-CVD). As a result, a selective overcladding is fabricated on the coupling part after the lift-off process. Fig. 2 shows a schematic view of the device we fabricated and scanning electron microscope (SEM) image. Almost perfect separation can be seen as a boundary between the SSC and graphene integration part.

3.! Devices characteristics

First, we confirmed that our fabrication process didn't cause any remarkable damage to the transferred graphene by μ-Raman spectroscopy. Next, we performed optical spectral measurement in the SSCs. Fig. 3 shows the spectra for tip widths of 150, 200 and 250 nm in (a) TE and (b) TM modes, acquired by using super luminescent diodes (SLDs). We obtained almost flat coupling properties for each tip width. At tip width of 200 nm, we observed broadband coupling of about 350 and 300 nm in TE and TM modes for 3-dB roll-off and the minimum coupling losses are 1.4 and 2.4 dB/facet at 1550 nm. These coupling losses are approximately 20% for TE and 14% for TM modes, as compared with our previous devices. Toward upcoming applications of graphene-integrated optical-electrical circuits and bio-chemical sensors, we integrated the SSCs onto a graphene integrated silicon-ring resonator which was measured without selective formed SSCs [5]. In this paper, we formed the SSCs in the device to confirm the coupling efficiency improvement. The silicon-ring resonator has a radius of 10µm and a 250-nm gap at the in and out directional couplers, and the graphene integrated on the left side of the ring is 5-µm long and 3-µm wide. A narrow bandwidth tunable laser diode and storage photodetector with a resolution of 1 pm was adopted to clarify the detailed spectral response in the TE mode. Fig. 4 compares spectral transmittance with and without SSCs of graphene-integrated silicon-ring resonators, and inset shows the device schematic. The peak transmittance improved about 10 dB, and resonance ripples are clearly suppressed by integrating SSCs.

4.! Conclusion

With a selective overcladding and inverse-taper waveguide formed on a graphene-integrated Si photonics platform, we demonstrated low coupling losses (1.4 and 2.4 dB/facet for TE and TM modes) and broadband coupling (over 350 and 300 nm in TE and TM modes) without causing damage to the single-layer graphene. We believe that our approach can contribute to future applications of graphene-integrated Si photonics.

References

1.!F. Bonaccorso *et al.*, "*Graphene photonics and optelectronics,*" *Nat. Photon*. **4**, pp. 611-622 (2010)
2.!M. Liu *et al.*, "*A graphene-based broadbanf optical modulator,*" *Nat. Photon.* **474**, pp. 64-67 (2011)
3.!Z. Cheng *et al.*, "*Spectral hole burning in silicon waveguides with a graphene layer on top,*" *Opt. Lett.* **38**, pp. 1930-1932 (2013)
4.!R. Kou *et al.*, "*Characterization of optical absorption and polarization dependence of single-layer graphene integrated on a silicon wire waveguide,*" *Jpn. J. Appl. Phys.* **52**, pp. 06203 (2013)
5.!R, Kou *et al.*, "*Influence of graphene on quality factor variation in a silicon ring resonator,*" *Appl. Phys. Lett.* **104**, pp. 091122 (2014)

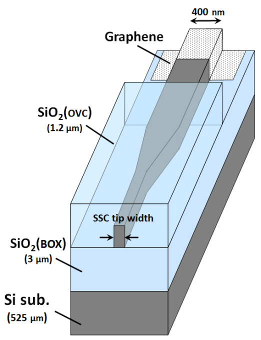

Fig. 1: Schematic view of selective SSC.

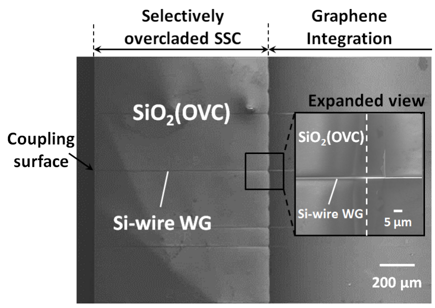

Fig. 2: Scanning electron microscope image of selective integrated part.

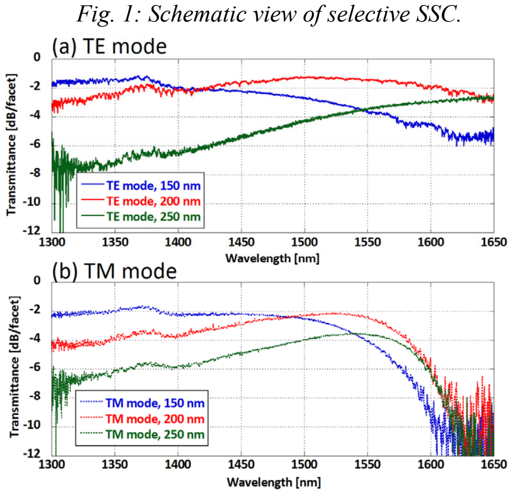

Fig. 3: Spectra for tip widths of 150, 200, 250 nm in (a) TE and (b) TM modes.

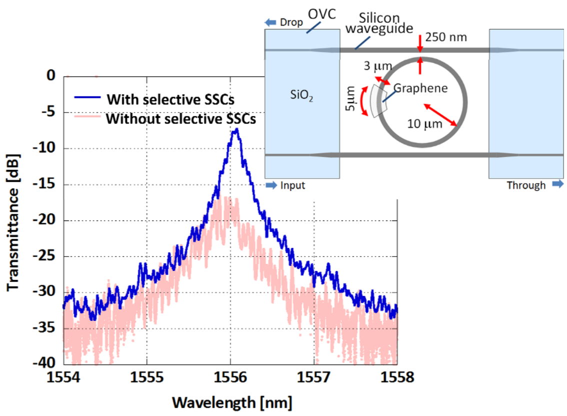

Fig. 4: Comparison of graphene integrated silicon-ring resonators for supression of ripples, and inset is the schematic.