ULTRA-COMPACT SILICON-GRAPHENE WAVEGUIDE DEVICE FOR HIGH-SPEED WAVELENGTH CONVERSION

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Keywords: WAVELENGTH CONVERSION, NONLINEAR OPTICAL DEVICES, FOUR-WAVE MIXING, INTEGRATED OPTICS DEVICES.

Abstract

We experimentally demonstrate an ultra-compact silicon-graphene wavelength converter at a 28-Gb/s data rate. A four-wave mixing conversion efficiency of −28 dB is achieved in the silicon-graphene strip waveguide with a 60-μm-long light-graphene interaction length using a moderate pump power.

1 Introduction

All-optical wavelength converters based on the four-wave mixing (FWM) offer an approach to realize high-speed signal processing without the optical-electrical-optical conversion process[1]. Benefitting from the low cost, compact footprint, and compatibility with the complementary metal-oxide-semiconductor (CMOS) fabrication process, silicon wavelength converters have attracted much attention for high-speed data processing[2-5]. However, these devices face the challenges of large footprints and high pump powers to ensure reasonable conversion efficiencies (CEs).

Graphene has a large Kerr coefficient, which is six orders of magnitude higher than that of the silicon[6], showing a great potential in the field of nonlinear optics. Combining the graphene with the silicon photonic device, a large effective nonlinearity can be expected, leading to an improved CE of the FWM process with a compact footprint at a low pump power. Recently, we reported an efficient and broadband FWM process in a silicon-graphene strip waveguide, showing an improved CE by 4.8 dB compared with a silicon strip waveguide with a 3-dB conversion bandwidth of 35 nm[7].

In this paper, we study the system performance of the silicon-graphene strip waveguide for wavelength conversion using a 28-Gb/s on-off keying (OOK) signal. The CE reaches −28 dB with a 60-μm graphene on silicon (GOS) waveguide, where the light-graphene interaction dominates the nonlinear process. The total length of the device is 3 mm with a 2.94-mm silicon waveguide for coupling, where the nonlinear effect is weak based on our previous calculation[7]. This is the shortest length of the non-resonant silicon device for high-speed wavelength conversion, to the best of our knowledge. In addition, the two-photon absorption (TPA) and free-carrier absorption (FCA) effects are not significant in the graphene layer, thus mitigating the pattern effect in the nonlinear conversion process.

2. Device fabrication and experimental setup

The proposed silicon-graphene strip waveguide was fabricated on a silicon-on-insulator (SOI) platform with a 220-nm-thick silicon layer and a 3-μm-thick silica layer. Fig. 1(a) illustrates the 3D view of the silicon-graphene strip waveguide, which consists of the GOS waveguide and the silicon waveguide under the silica layer. The length of the GOS waveguide, i.e. the interaction length between the graphene and the silicon waveguide, is determined by the size of the windowed silica layer on the silicon waveguide.

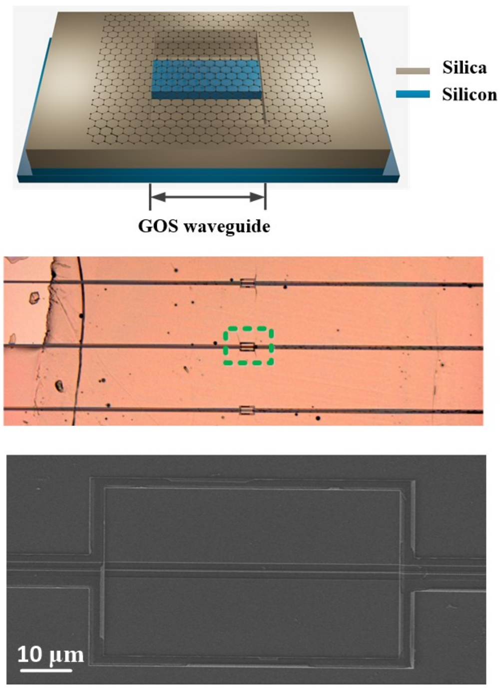

Fig. 1 (a) 3D view of the proposed silicon-graphene strip waveguide. (b) Micrograph of the fabricated silicon-graphene strip waveguides. (c) SEM image of the silica window, as labelled with the green block diagram in (b).

The micrograph and the scanning electron microscope (SEM) images of the fabricated devices are shown in Figs. 1(b) and 1(c), respectively. A numerical simulation analysis was used to study the effective nonlinearity in the GOS waveguide[7]. The calculated effective nonlinearity is 1.81×10^4 $(W \cdot m)^{-1}$, indicating that the GOS waveguide dominates the nonlinear process[7]. Therefore, an efficient FWM process can be achieved with an ultra-compact footprint.

Figure 2 presents the experimental setup for the all-optical wavelength conversion based on the degenerate FWM process. A continuous-wave (CW) light from a tunable laser (Southern Photonics TLS150D) is amplified by an erbium-doped fiber amplifier (EDFA, KEOPSYS CEFA-C-PB-HP) and serves as the pump source. The signal light from another tunable laser (Keysight 81960A) is modulated in a Mach-Zehnder modulator (MZM, FTM7939EK). An arbitrary waveform generator (AWG, Keysight M8195A) is used to produce the electrical signal to drive the MZM. The modulated 28-Gb/s OOK signal is amplified by anther EDFA (BA-27) and combined with the pump source through a 3-dB coupler. Two bandpass filters (BPFs) and polarization controllers (PCs) are employed to suppress the amplified spontaneous emission (ASE) noises and to make sure that the input lights are TE polarized, respectively. Then, two lensed single-mode fibers are used to couple lights into and out of the device under test (DUT) with a coupling loss of 6.7 dB/facet. To avoid the damage from the reflected light, an isolator is used before the DUT. The output light is split into two parts by a 50:50 optical splitter. One part is fed into an optical spectrum analyser (OSA, YOKOGAWA AQ6370C) to observe the output spectrum after the degenerate FWM process, while the other part is filtered by another BPF with the idler light retained. Due to the relatively low power of the idler, optical amplification and noise filtering are required before sending the idler light to a 40-GHz photodetector (PD, XPDV2120R) and an oscilloscope (LeCroy 10-36Zi-A). Since a large absorption loss is induced by the graphene sheet, the optimal light-graphene interaction length of 60 µm (the length of the GOS waveguide) is used in the experiment[7].

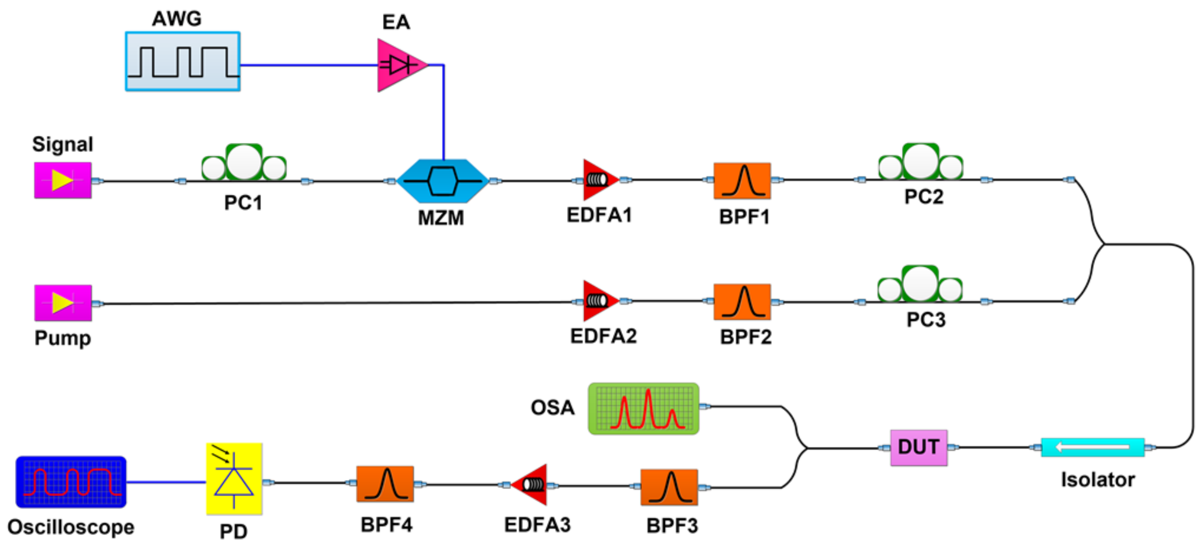

Fig. 2 Experimental setup for the all-optical wavelength conversion based on the degenerate FWM process. EA: electrical amplifier.

3 Results and discussions

Figure 3 plots the output spectrum of the silicon-graphene strip waveguide. The pump and signal wavelengths were located at 1549.68 nm and 1546.68 nm, respectively. The spectrum of the converted signal (Idler1) is broadened owing to the signal modulation, indicating that the converted signal is generated by the FWM process. Considering the losses induced by the PCs, the BPFs, the isolator and the fiber-to-chip coupling, the estimated input pump and signal powers were 18.3 dBm and 9.7 dBm, respectively. Here, the CE is defined as the ratio of the output idler1 power to the input signal power[9]. The measured CE is −28 dB by excluding a 6.7-dB per facet coupling loss. The CE is mainly contributed by the 60-µm-long silicon-graphene interaction section. Table 1 provides comparisons of our work with previously reported devices on a SOI platform. It can be seen that the proposed silicon-graphene wavelength converter enables a high-speed wavelength conversion with an ultra-compact footprint at a moderate pump power.

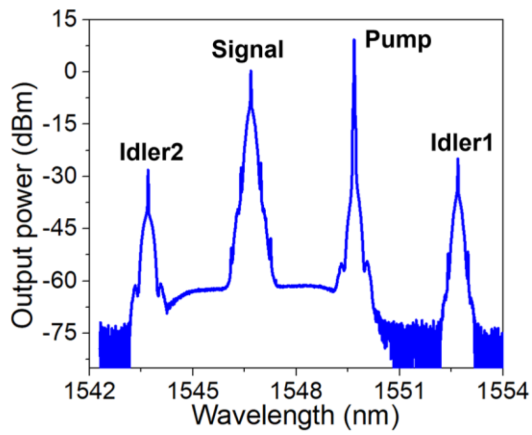

Fig. 3 Output spectrum of the silicon-graphene strip waveguide.

Table 1 Comparisons of the wavelength converters on a SOI platform

References	Interaction length	Pump power (dBm)	CE (dB)	Data rata (Gb/s)
Our work	60 μm[a]	18.3	-28	28
[2]	4 mm	16.6[b]	-32	>100
[3]	1.1 cm	24.1	-15.5	160
[4]	8 cm	26.5	-8.6	40

a: the total device length is 3 mm with a 60-μm silicon-graphene interaction length; b: an average on-chip pump power, the laser operates at a repetition of 42.7 GHz and emits pulses of ~3 ps full-width at half-maximum.

To evaluate the system performance, we measured the eye diagrams of the input signal and the converted signal carrying a 28-Gb/s data rate using an oscilloscope. As shown in Fig. 4, the eye of the converted signal remains open compared with that of the input signal. The Q-factor is defined as in Ref[10], and the calculated Q-factors of the signal and the idler are 24.3 and 21.2 dB, respectively. The eye diagram of the converted signal is widely open, indicating that the data rate can be further increased. The pattern effect is not obvious as the graphene does not show the TPA and FCA effects.

(a)

(b)

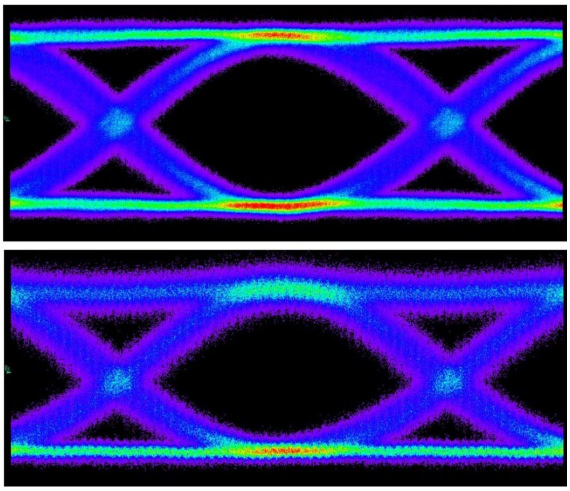

Fig. 4 Eye diagrams of the input signal (a) and the converted signal (b).

4 Conclusion

In summary, we have demonstrated an efficient wavelength conversion at a 28-Gb/s data rate in a silicon-graphene strip waveguide. Benefitting from the large effective nonlinearity of the GOS waveguide, the CE of the FWM process reaches −28 dB using a 60-μm-long light-graphene interaction length at a moderate pump power of 18.3 dBm.

5 Acknowledgements

This work was supported by the National Natural Science Foundation of China (NSFC) (61835008, 61605112). We thank the Center for Advanced Electronic Materials and Devices (AEMD) of Shanghai Jiao Tong University for the support in device fabrication.

6 References

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