# Spot-size-converter-integrated Directly Modulated Membrane Lasers on SiC for 100-GBaud PAM-4 Transmission over 2 km

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**Abstract** We demonstrate optical amplifier-free transmission over 2 km with 100-GBaud PAM-4 using a spot-size-converter-integrated directly modulated membrane laser on a SiC substrate. The spot-size converter using a SiO<sub>x</sub> waveguide is fabricated by partial removal of SiC, resulting in fibre-coupling loss of 2.7 dB. ©2023 The Authors

## Introduction

Data traffic and power consumption in data centres have been increasing due to various applications such as cloud and Internet of Things. Thus, optical transmitters in data centres must be energy efficient and fast. Directly modulated lasers (DMLs) are indispensable building blocks for short-reach optical communication, as they are compact, energy efficient, and low cost. However, the intrinsic 3dB bandwidth  $f_{3dB}$  is typically as low as 30 GHz, which is limited by a relaxation oscillation frequency  $f_r$  of 20 GHz.

To increase  $f_r$  by increasing the optical confinement factor  $\Gamma$ , we previously developed membrane lasers on 2-µm-thick SiO<sub>2</sub>/Si, in which the membrane InP layer that includes high-refractive-index multi-quantum wells (MQWs) is sandwiched between low-refractive-index SiO<sub>2</sub> layers [1,2]. This structure enables us to obtain high  $\Gamma$ , leading to low power consumption and high modulation efficiency. However, the thick and low-thermal-conductivity SiO<sub>2</sub> layer causes insufficient thermal dissipation, which limits the operation speed to standard values.

As a new platform that enables high thermal dissipation and  $\Gamma$ , we previously proposed membrane lasers on SiC with thermal conductivity and refractive index in the O-band of 490 Wm<sup>-1</sup>K<sup>-1</sup> and ~2.6, respectively [3]. With this structure, we succeeded in increasing fr to 42 GHz and  $f_{3dB}$  to 60 GHz for a 50-µm-long active region with a design to reduce the damping effect. We also achieved a  $f_{3dB}$  of ~110 GHz with the photon-photon resonance (PPR) effect generated by optical feedback from the output waveguide facet and demonstrated 256-Gbit/s PAM-4 at 25°C [3] and uncooled 100-Gbit/s NRZ modulation [4]. However, as the fibre-coupled output power was limited due to the high fibrecoupling loss of ~6 dB and short active length of 50 µm, we needed to use fibre amplifiers when transmitting the signal over 2 km. Toward

400-Gbit/s operation, the use of discrete multitone (DMT) modulation is also promising, however, our previous result was limited to 325 Gbit/s due to the limitation of signal-to-noise ratio [5]. To increase this, it is also important to increase the power coupled to the fibre in addition to reducing noise from electrical components [6].

In this context, we have to integrate a spotsize converter (SSC) to reduce the fibre-coupling loss and increase fibre-coupled power. For the membrane lasers on SiO<sub>2</sub>/Si, we previously fabricated a SiO<sub>x</sub>-based SSC, which enlarges the spot size of an InP output waveguide to the size of a fibre core [1]. Since the refractive index of SiC is larger than that of the SiO<sub>x</sub> core and SiO<sub>2</sub> overcladding layer, the optical mode disappears at the InP-tapered region on SiC. Namely, the spot size of the single-mode waveguide on SiC cannot be enlarged to that of the fibre core.

In this work, we addressed this issue by preparing the SiC substrate, where a given area was removed and filled with SiO<sub>2</sub>, and fabricating the SSC on it. The SSC enabled a 2.7-dB fibre coupling loss. To increase the output power, we enlarged the active length to 120  $\mu$ m while keeping the damping effect low. As a result, the fibre-coupled output power reached 7.3 dBm at 25°C and the intrinsic *f*<sub>3dB</sub> was kept high at 57 GHz. Thanks to these features, we



Fig. 1: Schematic of (a) top view and (b) side view of the fabricated membrane laser on SiC integrated with SSC.

demonstrated optical-amplifier-free 100-GBaud PAM-4 transmission over 2 km even without the PPR effect.

## Design and fabrication of device

Figures 1(a) and (b) respectively show a schematic diagram of the top view and side view of the fabricated SSC-integrated membrane laser on SiC. To fabricate the SSC on SiC, we have to meet the following requirements: i) the SiC has to be partially removed to fabricate the SSC, ii) the thickness of SiO<sub>2</sub> under the active region has to be thin to maintain high thermal conductivity, and iii) the surface of SiO<sub>2</sub> has to be flat to allow the direct bonding of the III-V layer. The SSC included the inversely tapered InP waveguide and SiO<sub>x</sub> core, the dimension of which is suitable to match an optical mode field of a single-mode high-numerical-aperture fibre (HNAF). At the InP tapered region, the optical-mode field is gradually transited into the SiO<sub>x</sub> core. The laser light from the active core is coupled to the SSC with a 5-µm-long InP waveguide. We designed a distributed reflector (DR) laser consisting of a 120-µm-long DFB section and 120-µm-long distributed Bragg reflector (DBR) mirror. The DBR mirror selects one of the DFB lasing modes, enabling single-mode operation. The active region consists of nine-period InGaAlAs-based MQWs. In our previous study [3], we reduced the damping effect by increasing (shortening) the mirror loss (the photon lifetime) for the 50-µm-long active region with a reduced grating coupling coefficient  $\kappa$  of 600 cm<sup>-1</sup>. In this study, to reduce the damping effect for the 120-µm-long active region, we further reduced  $\kappa$  to 250 cm<sup>-1</sup> and set mirror loss to ~45 cm<sup>-1</sup>. Based on the calculation results for small-signal responses at fr of ~40 GHz [3], the damping effect was well suppressed at mirror losses of >40 cm<sup>-1</sup>, enabling  $f_{3dB}$  to reach >50 GHz.

The fabrication procedure of the SSCintegrated membrane laser on SiC is as follows. First, we prepared a 2-inch SiC substrate. After



2-µm dry etching for a given area where the SSC will be integrated, we deposited SiO<sub>2</sub> to fill the dip. Note that the 2- $\mu$ m-thick SiO<sub>2</sub> is sufficient for the undercladding layer because we previously fabricated the SSC on 2-µm-thick SiO<sub>2</sub>/Si [1]. We polished the surface by chemical mechanical polishing (CMP) to thin and flatten the SiO<sub>2</sub> film. To achieve high thermal dissipation at the active region, we carefully carried out CMP so that the thickness of the rest of the SiO<sub>2</sub> layer on the SiC substrate would be ~30 nm. Next, the SiC substrate was bonded to a 2-inch InP substrate that included MQWs using the O<sub>2</sub>-plasma assisted-bonding technique. Since we deposited a 5-nm SiO<sub>2</sub> film on the InP substrate as an intermediate bonding layer, the intermediate SiO<sub>2</sub> layer thickness between the active region and SiC is roughly estimated to be ~35 nm. The subsequent laser-fabrication processes up to the electrode formation was almost the same as in our previous study [3]. We then deposited the SiO<sub>x</sub> core layer. By partially removing the SiO<sub>x</sub> layer using reactive ion etching, the SiO<sub>x</sub> core was defined. Finally, a 5-µm SiO<sub>2</sub> overcladding layer was formed on the SSC, followed by opening the contact holes for electrodes.

## **Results and discussion**

Figure 2 shows the measured output light versus bias current (L-I curves) at  $25^{\circ}$ C; one curve for detecting output power using a photodetector (PD) placed in front of the output facet and the other for detecting output power using a single-mode HNAF that was butt-coupled with the SiO<sub>x</sub> waveguide facet (blue). All the following measurements were carried out at  $25^{\circ}$ C. The reflection at the facet caused kinks in the L-I curve measured using the PD. On the other hand, when the HNAF was butt-coupled, the reflection at the edge was suppressed and the kink was not significant. The threshold current was 2.7 mA. The output power detected using the PD reached 10.3 mW (10 dBm) thanks to the enlarged active



Fig. 3: Lasing spectrum at 25°C and 80 mA. Inset: lasing wavelength against the input electrical power.



Fig. 4: Small-signal S<sub>21</sub> response at 25°C and 80 mA.

length of 120  $\mu$ m. The maximum fibre-coupled output power reached 5.4 mW (7.3 dBm). The fibre-coupling loss at 80 mA was evaluated as 10-7.3 = 2.7 dB, which is almost identical to those obtained for SSC-integrated membrane lasers on SiO<sub>2</sub>/Si [1,2]. Increased output power and bias currents also indicate that self-heating effect is suppressed, which evidences the thin SiO<sub>2</sub> intermediate layer.

Figure 3 shows the lasing spectrum at 80 mA. The shorter side mode of the DFB stopband was selected, achieving single-mode lasing. From the spectrum fitting.  $\kappa$  was almost identical to the designed value of 250 cm<sup>-1</sup>. No interference was observed in the DFB stopband, which means that the reflection (e.g., possibly occurring at the InP tapered edge, front of SiOx waveguide, output SiO<sub>x</sub> facet, etc.) was sufficiently small. The inset in Fig. 3 shows the lasing wavelength against the input electrical power. The wavelength was lineally changed, indicating that there was no mode hop. Figure 4 shows the small-signal S<sub>21</sub> response at 80 mA measured using a light component analyser (Keysight N4373D). We were able to obtain a  $f_{3dB}$  of 57 GHz thanks to the high  $f_r$  and suppressed damping effect for the laser with the 120-µm-long active region.

Figure 5(a) shows the experimental setup for evaluating the bit-error rate (BER). The 100-GBaud PAM-4 signals were generated using waveform arbitrarv generator (AWG) an (Keysight M8199A) at 200 GSa/s with an analog f<sub>3dB</sub> of 70 GHz. We used an external 66-GHz amplifier with an 11-dB gain (SHF M827B). The laser was driven using a 65-GHz bias tee and 67-GHz RF probe. The optical power was detected with an in-house uni-traveling-carrier (UTC) PD module with a  $f_{3dB}$  of ~90 GHz. The received electrical signal with the PD was amplified with an external electrical amplifier (SHF M827B) and then captured using a realtime digital storage oscilloscope (DSO) with a sampling rate of 256 GSa/s and bandwidth of 110 GHz. We used a 9-tap linear equalizer to compensate for distortions. Note that we did not use an optical amplifier. Figure 5(b) shows the



Fig. 5: (a) Experimental setup. (b) BER vs. ROP for the 100-GBaud PAM-4 signal transmission. 100-GBaud PAM-4 equalized optical eye diagrams (c) for BTB and (d) after 2km SSMF transmission.

BER versus received optical power (ROP) for back-to-back (BTB) and 2-km transmissions of 100-GBaud PAM-4 signals, where the equalized optical eye diagrams for BTB and after 2-km standard-single-mode fibre (SSMF) transmission are shown in Figs. 5(c) and (d), respectively. The bias current, bias voltage, and peak-to-peak voltage were 80 mA, 3.04 V, and 2.77 V, respectively. The BERs were less than the 6.7%overhead hard-decision forward error correction (HD-FEC) threshold of 3.8×10<sup>-3</sup> [7]. We observed lower BERs after the 2-km transmission than the BTB. This fact was confirmed in the previous measurements due to the negative dispersion of the SSMF [3,4]. The energy cost was calculated to be 1.3 pJ/bit. The previous highest modulation speed for DMLs without the PPR effect was 56-GBaud PAM-4 using InGaAlAs lasers with a ridge-shaped buried-heterostructure fabricated on InP [8]. We demonstrated 100-GBaud modulation using our DML without the PPR effect for the first time, thanks to the improved fibrecoupled output power and large bandwidth. The next step is to use the PPR effect for our SSCintegrated membrane laser on SiC and achieve a higher bit rate and lower power consumption.

#### Conclusions

We fabricated a membrane laser on a SiC substrate integrated with a SSC, where, below the SSC, SiO<sub>2</sub> was formed in advance. We improved the fibre-coupling loss to 2.7 dB and achieved 7.3-dBm fibre-coupled power while maintaining a large bandwidth at 57 GHz. We also demonstrated the optical-amplifier-free 2-km transmission of 100-GBaud PAM-4 signals. Such DMLs are promising for beyond 400-Gbit/s Ethernet.

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