Novel reflective SOA with MMI-loop mirror based on semi-insulating InP

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The reflective SOA has been heavily investigated to carry the upstream signal for colorless operation in the user access network. We propose a new method to realize such a reflective SOA modulator by integrating a SOA with a MMI-loop mirror (loop-RSOA). This allows for more flexibility in the design of photonic integrated circuits without additional cost. The first loop-RSOA has been designed and fabricated. The fiber access side of the loop-RSOA was left as cleaved. The measurement results show that this loop-RSOA can be operated error free with 1.25 Gbit/s data with $2^{23}-1$ *PRBS word length while the injected optical power is* -14 *dBm. Furthermore, the temperature dependence of the loop-RSOA has been investigated from* $12°\mathrm{C}$ *up to* $36°\mathrm{C}$ *showing Q factors higher than 6.5 at 1 Gbit/s.*

Introduction

Reflective SOA has been heavily investigated in the fiber-to-the-customer network to achieve Gigabit upstream data operation [1, 2]. The advantage of employing RSOA instead of a wavelength-specific laser is "colorless" operation, thus cost effective in the network operation and maintenance [3]. A reflective SOA together with electro-absorption modulator (EAM) [4] has upgraded the data rate up to 5 Gbit/s. The commonly used method to make the device reflective is applying high-reflection (HR) coating at the output facet of the chip. The advantage of this method is that the reflectivity can be chosen flexibly by applying different layers of coating. However, HR coating is normally at the facet, and the HR coated facet can not be used as output port for other components any more, thus it hinders the flexibility in the design of the photonic integration circuits (PIC).

In this paper, we will introduce another method to fabricate a reflective SOA, SOA integrated with a MMI-loop mirror, Fig. 1 (left). Comparing with HR coating, this MMI-loop mirror offers more flexibility in the design of PIC without additional cost. It can be employed for any component at any position, and it is formed during the SOA fabrication. In principle, the reflectivity of the MMI-loop mirror is 100%, apart from fabrication issues and wavelength dependent losses in the 3 dB MMI splitter/combiner.

In the following sections, we present the design and simulation of the MMI-loop mirror, fabrication of the loop RSOA, and measurement results of the loop RSOA. Finally, the conclusion and the discussion will be issued.

Simulation and design

The MMI loop mirror is composed of a 3 dB 1×2 MMI splitter/combiner and curved waveguides, Fig. 1(left). The 3 dB MMI is designed 8 μm wide and 67 μm long, deeply etched with 2.5 μm wide access waveguides which are connected with 1.5 μm wide deeply etched narrow curved waveguides through adiabatic linear tapers. The radius of

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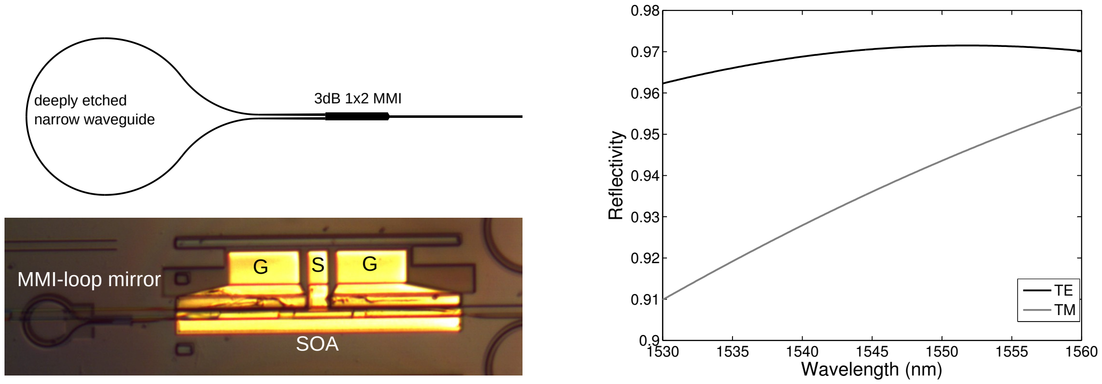

Figure 1: Left: Mask layout of a MMI-loop mirror and a fabricated reflective SOA integrated with MMI-loop mirror. Right: The simulated reflectivity of the MMI-loop mirror as a function of the wavelength for both TE and TM polarization.

the curved waveguides is 80 μm. The simulated reflectivities of the MMI-loop mirror for both TE and TM polarization is shown in Fig. 1(right). The simulation result shows that the reflectivity can be more than 90% for a wavelength range of 1530 nm to 1560 nm for both TE and TM polarization.

The whole device is based on semi-insulating (SI) InP substrate, mainly for the future monolithic integration with a high-bandwidth photodetector and a high-frequency modulator. Therefore the lateral N-contact is needed, as shown in Fig. 1 (lower left). The SOA is 2 μm wide and 1000 μm long, shallowly etched. The waveguide entering and exiting the SOA is adiabatically angled with 12° to minimize the undesired reflectivity at the active-passive butt-joint [5]. The signal feed lines are designed with ground-signal-ground (GSG) layout for the direct dynamic characterization with RF probes. They were tapered to the lateral N-contacts and P-contact of the SOAs. Below the GSG probe pads and the feed lines, all the conductive semiconductor materials were etched away to reduce the microwave attenuation, and later this region was planarized with the polyimide.

Fabrication

The reflective loop-SOA is based on the layer stack shown in Fig. 2(left). The epitaxial material was grown on a SI-InP substrate by three-step low pressure metal-organic-vapor-phase epitaxy (MOVPE) at 625°C. The first epitaxy finished with a 120 nm thick SOA active InGaAsP layer (Q1.55, $\lambda_{gap} = 1.55\,\mu$m), embedded between two quaternary confinement layers (Q1.25) with different doping levels, covered by a 200 nm thick p-InP layer. Next, the active sections were defined by lithography, and the passive part was wet chemically etched about 50 nm below Q1.55. In the second epitaxy step, a Q1.25 InGaAsP layer was selectively grown for the passive sections. In the third epitaxy step, common 1300 nm p-doped InP cladding layers and the 300 nm thick p-InGaAs contact layer were grown. The typical reflectivity at butt-joint is lower than -50 dB with angled entry and exit waveguide, and the transmission loss is lower than 0.19 dB [5]. The cross section of the fabricated SOA is shown in Fig. 2(right). One side of the fabricated loop RSOA is left as cleaved, which has about 30% (26%) reflectivity for TE (TM) polarization, in order to locate the main reflection cavities. The total cavity length including the mirror is 1930 μm.

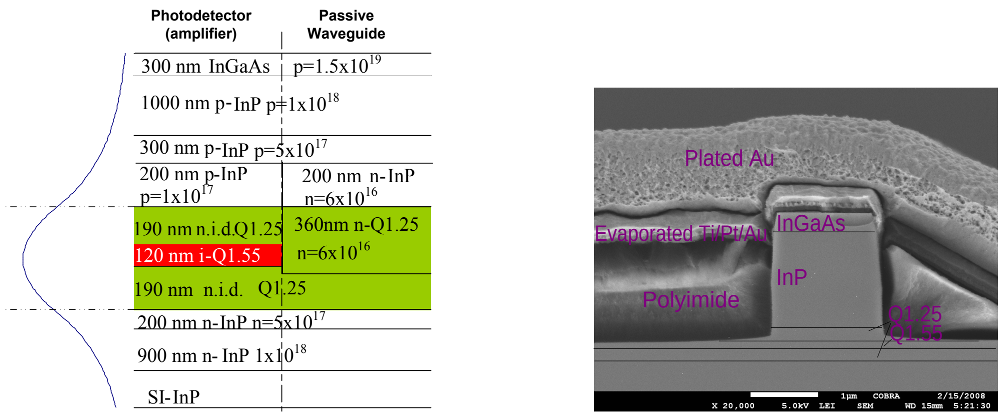

Figure 2: Left: Active-passive butt-joint layer stack with specifications based on a semi-insulating substrate, and the transverse mode-profile is shown. Right: Cross section of the fabricated SOA.

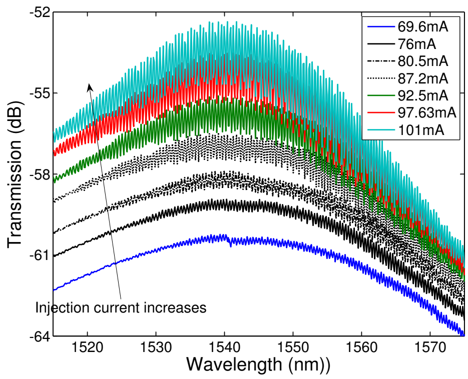

Figure 3: The output ASE spectrum with 0.05 nm resolution of optical spectrum analyzer at different injection currents at 25°C.

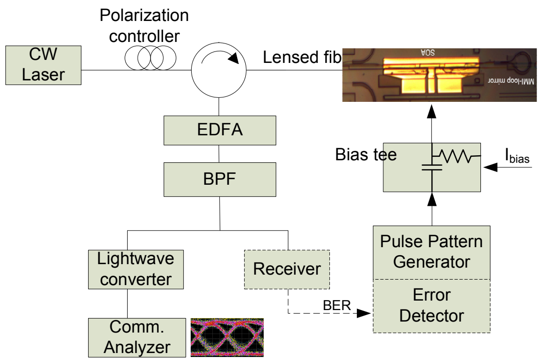

Figure 4: Eye diagram and BER measurement setup for the loop RSOA.

Characterisation

The measured reflectivity of the test loop mirror is about 60%~70%, corresponding to 2 dB~1.5 dB total loss. The measured ASE spectrum of the loop RSOA at different injection currents are shown in Fig. 3. The mode spacing of the ripple is 0.167 nm corresponding to the cavity length mentioned before. The gain ripple is less than 1 dB when the injection current is lower than 87 mA. The dynamic measurement has been carried out in the measurement setup shown in Fig. 4. We used a tunable laser as CW light source, and the polarization state is controlled by the polarization controller. The light was directly modulated through the loop RSOA with 1.25 Gbit/s NRZ data. The pattern length is $2^{23}-1$ pseudo-random binary sequence (PRBS). The DC bias was kept at 81 mA where the chip gain is about 15 dB and the measured saturation input optical power is higher than -9 dBm. The modulation amplitude was set at 250 mV in the pattern generator (PPG). The Q factor of the measured eye are 6 (5) for -11 dBm (-14 dBm) injected optical power. The eye diagram was obtained by converting the modulated optical signal into an electrical signal through a lightwave converter, and recorded by a digital communication analyzer. The back-to-back BER measurement at 1.25 Gbit/s has been carried out through a commercial receiver for different injected optical power level before the fiber-chip coupling, shown in Fig. 5(left).

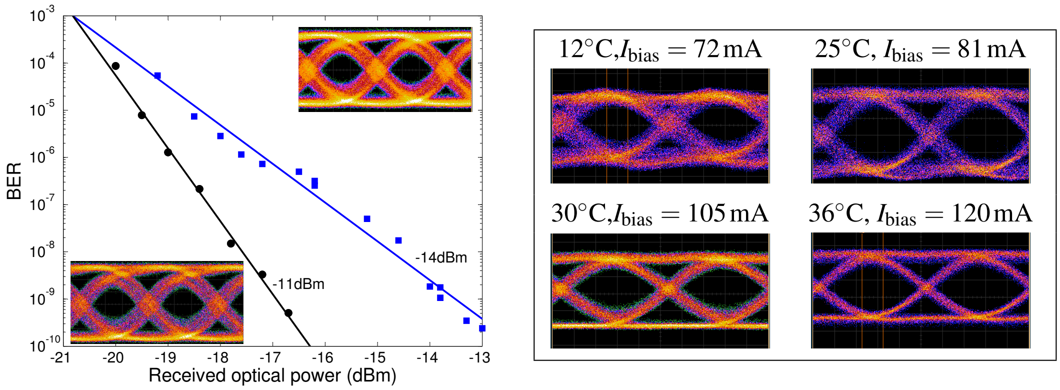

Figure 5: Left: Measured BER performance at 1.25 Gbit/s for different injected optical power level. The measured eye diagrams at 1 Gbit/s for 1555 nm at different temperatures. Right: The input optical power is −9 dBm, and the modulation amplitude is 250 mV.

To further investigate the stability of the device under different temperatures, we kept the input light wavelength at 1555 nm, the injected optical power at −9 dBm and the modulation amplitude constant at 250 mV. The temperature was set through the Peltier element from 12°C to 36°C. The recorded eye diagrams are presented in Fig. 4. All the eyes are clearly open, the Q factors of the eyes are higher than 6.5, and the extinction ratio is higher than 5 dB.

Conclusion and discussion

We have proposed and successfully demonstrated a new method to realize a reflective SOA: a SOA integrated with a MMI-loop mirror, which can operate error free for 1.25 Gbit/s data with $2^{23} - 1$ PRBS with −14 dBm injected optical power before the chip. Furthermore, this device can operate with a Q factor higher than 6.5 and extinction ratio higher than 5 dB from 12°C to 36°C at 1 Gbit/s. The MMI-loop mirror can be applied flexibly at any component integrated in the circuit which needs high reflectivity at one port without disturbing the output ports of other components. The reflectivity of this loop mirror can be enhanced by optimizing the fabrication to reduce the waveguide transmission loss. The performance of such a loop RSOA can be further improved by applying anti-reflection coating at the fiber access side to obtain higher chip gain.

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