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Monolithically Integrated Laser Diode and Electroabsorption Modulator with Dual-Waveguide Spot-Size Converter Output *

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Abstract: A 1.60μm laser diode and electroabsorption modulator monolithically integrated with a novel dual-waveguide spot-size converter output for low-loss coupling to a cleaved single-mode optical fiber are demonstrated. The devices emit in a single transverse and quasi single longitudinal mode with an SMSR of 25.6dB. These devices exhibit a 3dB modulation bandwidth of 15.0GHz, and modulator DC extinction ratios of 16.2dB. The output beam divergence angles of the spot-size converter in the horizontal and vertical directions are as small as 7.3°×18.0°, respectively, resulting in a 3.0dB coupling loss with a cleaved single-mode optical fiber.

Key words: laser diode; electroabsorption modulator; spot-size converter; integrated optoelectronics; optical coupling

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1 Introduction

In recent years, an electroabsorption modulator (EAM) which operates using the quantum-confined Stark effect (QCSE) is attractive as an external modulator because of its many features, such as low power consumption, low drive voltage, small size, large modulation bandwidth, polarization-insensitivity, and potential for monolithic integration with other components[1~3]. An optical device integrated with a spot-size converter (SSC) has also been paid more attention for its direct coupling to an optical fiber with low-loss coupling, large alignment tolerances, and simple packaging schemes without using a micro-lens or tapered fiber[4]. Monolithic integration of a laser diode (or semiconductor optical amplifier) and the EAM with a SSC output (LD-EAM-SSC) is much more attractive for a transmitter module in the optical fiber communication system. This is because of its low-cost packaging due to its large spot size which is well matched to that of a single-mode fiber (SMF)[5~9]. However, most of them are based on buried structure with or without selective area growth (SAG)[3,5,6]. Moreover, most of them involve complex growth steps, excessive processing steps, strict process tolerance, and poor device performance. In

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this paper, a 1.60μm novel LD-EAM-SSC is fabricated by selective area growth and dual-core technology. For the LD-EAM section, a double ridge structure is employed. A ridge structure also exhibits very low capacitances, which enables, for example, high bit-rate operation in integrated laser-modulators[10]. For the SSC section, a buried ridge double-core structure (BRS) is incorporated. The combination of the ridge and BRS structure can take advantage of both the easy processing of the ridge structure and the excellent mode characteristic of the BRS. This is the first time that such a structure is reported, as far as we know. Furthermore, the novel LD-EAM-SSC was easily fabricated using only three steps low-pressure metal-organic vapor phase epitaxial (LP-MOVPE) growth and a conventional photolithography and wet etching process. More important, the device emits in a single transverse mode and quasi single longitudinal mode with a side mode suppression ratio (SMSR) of 25.6dB, although no grating is fabricated in the LD region. Furthermore, these devices exhibit a 3dB modulation bandwidth of 15.0GHz, and modulator DC extinction ratios of 16.2dB. The output beam divergence angles of the spot-size converter in the horizontal and vertical directions are as small as 7.3°×18.0°, respectively, resulting in a 3.0dB coupling loss with a cleaved single-mode optical fiber. All the performance indexes are as good as or better than those of other counterparts[3,5,6].

2 Device structure and fabrication

Figure 1 shows the schematic structure of the LD-EAM-SSC. The output end of the device has a 300μm-long dual-waveguide SSC, for which the active core is linearly tapered from 3μm to 0μm along with the propagation direction while its passive core is 8μm-wide and 50nm-thick, a 0.2μm InP space layer between them. So in the LD and EAM section most optical power is confined in the active core. However, in the SSC section, the optical power is gradually transferred to the passive core along with the SSC active core becoming narrow. Eventually, at the output facet of SSC, the optical mode is determined only by the thin passive core, which is designed to expand and stabilize the beam from the LD and EAM for efficient coupling to an SMF. Followed the SSC regions are the LD and EAM sections. The LD and EAM sections are 600μm-long and 150μm-long, respectively, with a 50μm-long etched electrical isolation region between them. A conventional double ridge waveguide structure is used for the LD and EAM region. However, a buried ridge double-core structure (BRS) is incorporated for the SSC regions.

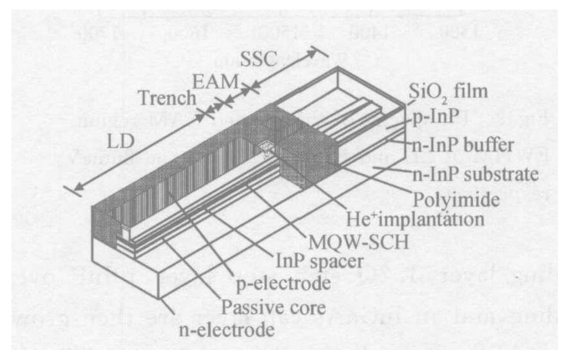


Fig. 1 Schematic diagram of the LD-EAM-SSC

The LD-EAM-SSC is fabricated using a only three-step LP-MOVPE process, one of which is the SAG step. For the first epitaxial growth, InP buffer, 50nm-thick n-type 1.15μm bandgap InGaAsP quaternary (Q) lower waveguide and a 0.2μm n-InP spacer layer are grown. Then, two SiO_2 pads are patterned on the spacer layer in the LD region. The MQW-SCH stack is then grown. The MQW structure consists of ten strained InGaAsP quantum wells and nine InGaAsP barriers, SCH layers (100nm, λ = 1.2μm) on both sides of the MQW-layer. The oxide pads cause an enhancement of the growth rate and a reduction of the bandgap energy of the Q-waveguide in the middle of the gap between the oxide pads. The SAG process creates a bandgap difference between the modulator and the laser diode of 75nm as measured with small-spot photoluminescence (see Fig. 2). After removing the SiO_2, the lateral taper is formed by selective etch-

ant of MQW-SCH layers from the SSC regions. A sharp taper tip less than 0.4μm at the SSC section is easily achieved by normal photolithography combined with an undercut etching. So, there is no need for a submicron pattering using expensive and time-consuming e-beam lithography. A thin p-InP

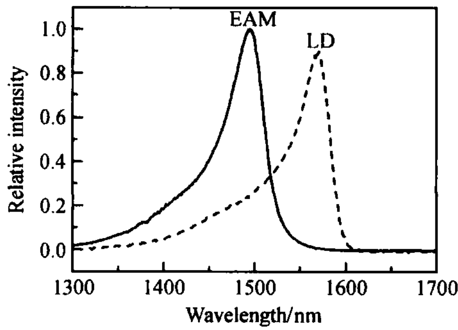


Fig. 2 PL spectra of the LD and EAM region FWHM of LD and EAM is 27meV and 26meV, respectively.

cladding layer, 1.2Q etch stop layer, p-InP overcladding, and an InGaAs cap layer are then grown in the third epitaxial growth step. This is followed by conventional double ridge waveguide processing of the LD and EAM sections. The width of the LD and EAM upper mesa and the maximum width of the lower mesa are 3μm and 8μm, respectively (see Fig. 3). The LD and EAM are electrically isolated by etching away the highly conductive InGaAs cap layers between the two sections and He^+ is implanted in the trench. Figure 1 illustrates these described features. To eliminate the excess light ab-

Fig. 3 SEM picture of EAM transverse section

sorption in the InGaAs cap layer (lattice matched InGaAs has an absorption wavelength of 1.67μm) in the SSC regions, the InGaAs cap layer in the SSC region is entirely etched away. A SiO_2 dielectric layer is then deposited on the wafer. Polyimide is defined on either side of the LD and EAM mesa for planarization of its ridge structure and reduction of EAM spurious capacitance of the p contact pads to enhance the modulation bandwidth. After a contact hole is etched on the top of the LD and EAM ridges, standard p- and n-metal layers are evaporated.

3 Device performance

The typical lasing wavelength of the LD-EAM-SSC is around 1.60μm at 25 ℃ and the breakdown voltage of the EAM is at -10V. Isolation electric resistance between the LD and EAM section is more than 100kΩ while the total EAM capacitance is 0.4pF at a reverse bias of 2V which leads to a 3dB modulation bandwidth of 15.0GHz.

Figure 4 shows the laser typical optical spectrum of the device at 198mA and 25 ℃ when the EAM biased voltage is 0V. Quasi single longitudinal mode is observed with an SMSR of 25.6dB, although no grating is fabricated in the LD region. This is probably because the interfaces among the LD, EAM, and SSC divide the whole cavity length into some sub-sections, and the optical frequencies that are resonant with any of the sub-section lengths are enhanced. The mode selection is caused

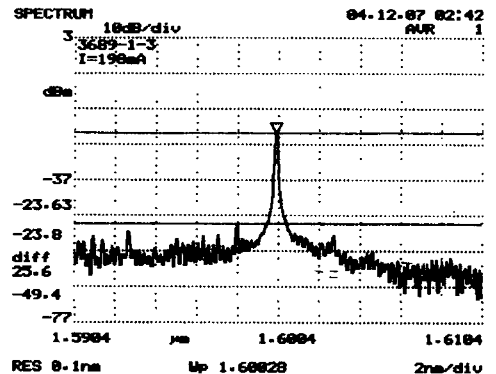


Fig. 4 Emission spectrum of the LD-EAM-SSC

by refraction of the mode on the scale of the cavity rather than by diffraction at the scale of the emission wavelength.

Figure 5 shows the function of SMSR versus the LD drive current. As the current is increased, the SMSR is increased to 25.7dB at 180mA. Further increase in the current causes the SMSR to decrease. At the same time, the lasing wavelength of the LD-EAM-SSC is almost around 1.60μm as long as the temperature is kept at 25 ℃.

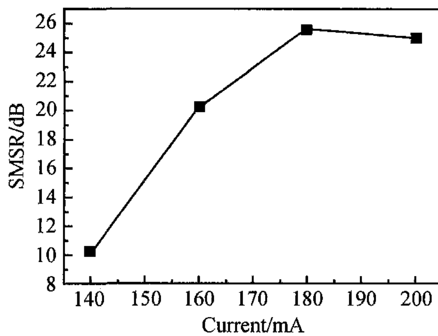


Fig.5 SMSR versus LD drive current

Figure 6 shows the *P-I* characteristics of the device when the modulator is biased. There is no significant degradation of the threshold and the output light power observed in the integrated devices with a different length of SSC the region in the same wafer, which indicates that there is no large excess absorption loss at the introduction of the SSC. As can be seen in this figure, as the reverse bias voltage increases, the threshold current of the device increases monotonically. This threshold current increment is due to the electroabsorption induced by the reverse bias on the modulator. Note the abrupt turning on of the *P-I* characteristics which is a common feature of this kind of devices. From these *P-I* characteristics, one can see that when the bias voltage on the modulator is varied from 0 to -2.5V while the current injection on the laser is fixed at 160mA, the on-off ratio is larger than 16.2 ∶1, normally on operation.

Figure 7 shows the far field pattern observed from the SSC facet and that from the rear facet of the LD (In Fig.7(b), there is a side lobe at an an-

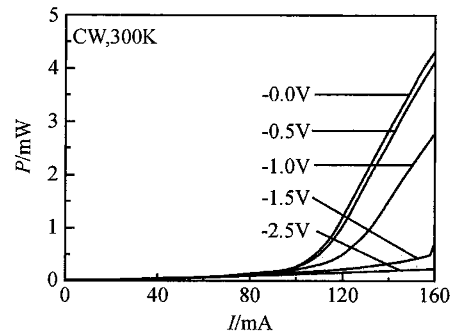
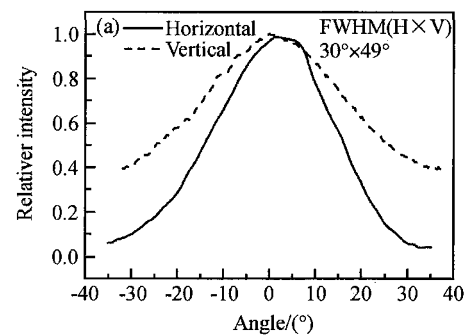


Fig.6 *P-I* characteristics of the device when the modulator is biased



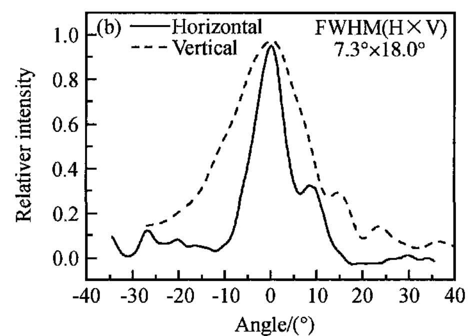


Fig.7 Far-field pattern from the laser rear facet (a) and SSC facet (b)

gle of 10° in a horizontal FFP, which is caused by the reflected light from the submount). As can be seen in this figure, the LD-EAM-SSC emits in a single transverse mode, which indicates that there is no degradation of single transverse mode characteristics at the introduction of the SSC. The divergence angles from the SSC facet are as small as 7.3°×18.0° in the horizontal and vertical directions, respectively. In contrary, those from the rear facet of the LD are as large as 30.0° and 49°. The coupling loss and 1dB align tolerance for the SSC

facet are about 3.0dB, ±3.1μm (horizontal) × ±2.65μm (vertical), when the device is coupled to a cleaved SMF. However, at the same case, those from the rear facet of the LD are about 9dB, ±2.0 μm (horizontal) × ±1.7μm (vertical).

4 Conclusion

A 1.60μm laser diode and electroabsorption modulator monolithically integrated with a novel dual-core spot-size converter output for low-loss coupling to a cleaved single-mode optical fiber is demonstrated. The devices emit in a single transverse and quasi single longitudinal mode with an SMSR of 25.6dB. The DC extinction ratio of 16.2dB is observed for the device with a modulator bias of 2.5V. The output beam divergence angles of the spot-size are as small as 7.3°×18.0°, in the horizontal and vertical directions, respectively, resulting in low-coupling losses with a cleaved optical fiber (3.0dB loss). Simple fabrication procedure and excellent performance make the device suitable for mass-production and a cost-effective active, or passive, mode locked laser[11,12]. If both side of mirrors are AR coated, the device will become the structure of SOA-EAM-SSC, which offers a single compact device incorporating both signal amplifier and modulation functions as well as spot-size conversion.

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半导体激光器电吸收调制器和双波导模斑转换器的单片集成*

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摘要: 报道了 1.6μm 的半导体激光器和电吸收调制器以及双波导模斑转换器的单片集成器件. 该器件具有良好的单横模特性和准单纵模特性(边模抑制比达 25.6dB), 3dB 调制带宽为 15GHz, 直流消光比为 16.2dB, 远场发散角为 7.3°×18.0°, 和单模光纤的耦合效率达 3.0dB.

关键词: 半导体激光器; 电吸收调制器; 模斑转换器; 光电子集成; 光耦合

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