An Electroabsorption Modulator Monolithically Integrated with a Semiconductor Optical Amplifier and a Dual-Waveguide Spot-Size Converter*

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Abstract: A semiconductor optical amplifier and electroabsorption modulator monolithically integrated with a spot-size converter input and output is fabricated by means of selective area growth, quantum well intermixing, and asymmetric twin waveguide technology. A 1550～1600nm lossless operation with a high DC extinction ratio of 25dB and more than 10GHz 3dB bandwidth are successfully achieved. The output beam divergence angles of the device 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: semiconductor optical amplifier; electroabsorption modulator; spot-size converters; selective area growth; quantum well intermixing; asymmetric twin waveguide

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1 Introduction

Wavelength-division multiplexing (WDM) is now an enabling technology to meet the boosting capacity of optical transmission systems. Advanced WDM networks must have various functional components, such as modulator, routing, switching, and wavelength add-drop multiplexing, etc. As a result, monolithic integration components with a variety of active and passive photonic devices are becoming increasingly attractive, due to their miniaturized multifunction optical circuits, compactness, low-cost batch fabrication, and high stability. A semiconductor optical amplifier (SOA) integrated with an electroabsorption modulator (EAM) is promising for a high-performance modulator, because the SOA can compensate for the inevitable insertion loss of the EAM and coupling loss to a fiber[1～3]. Monolithically integrated SOA and EAM with spot-size converters (SSC) input and output have been paid more attention for their 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[4～6]. However, most of them have been based on buried structure with selective area growth (SAG) or butt-joint selective area growth (BJ-SAG) tech-

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nique, which involves complex growth steps, excessive processing steps, and strict process tolerance. In this paper, a novel structure with a relatively simple fabricating approach is demonstrated in which SAG, quantum well intermixing (QWI), and asymmetric twin waveguide (ATG) technologies are successfully used. For the SOA/EAM section, SAG technology is employed to exactly control the bandgap difference of the SOA gain peak and the exciton absorption edge. For the input and output SSC sections, QWI is used to make the bandgap blue-shifted as far as possible from the EAM material to reduce the direct bandgap absorption, while ATG technology is employed to expand the mode spot size to match the core of a single-mode fiber (SMF). By contrast with BJ-SAG technique, QWI allows for strategic post-growth tuning of the QW band edge in a relatively simple procedure. Also, QWI does not change the average composition and only slightly changes the compositional profile, so there is a negligible index discontinuity at the interface between adjacent sections. Thus it eliminates harmful parasitic reflections that can degrade performance[7]. A low-energy P^+ ion-implantation-induced intermixing method is used in this work. For the so-called ATG structure, the active waveguide is laterally tapered and combined with an underling passive waveguide. Such a combination makes it easy to control the beam divergence at the output facet. Furthermore, ATG technology is robust, low-loss, compatible with existing epitaxial designs, and uses fabrication techniques that are common in InP laser manufacturing. For the device structure, double ridge structure is employed in the SOA/EAM section. A ridge structure exhibits very low capacitances, which enables high bit-rate operation in integrated laser-modulators. For the SSC sections, a buried ridge double-core structure (BRS) is incorporated. Such a combination of ridge and BRS structure, in which SAG, QWI, and ATG technologies are successfully used, is reported for the first time.

2 Device structure and fabrication

Figure 1 shows the schematic structure of the device. The input and output end of the device have a 300μm-long dual-waveguide SSC, whose active core is linearly tapered from 3 to 0μm along with the propagation direction, while its passive core is a 8μm-wide and 50nm-thick rectangular waveguide, with a 0.2μm InP space layer between them. In the SOA/EAM section, most optical power is confined in the active core. However, in the SSC section, the optical power is gradually transferred, along with the light transmission direction, from the tapered active core to the passive one. Eventually, at the output facet of the SSC, the optical mode is determined only by the thin passive core, which is designed to expand and stabilize the beam from the SOA/EAM for efficient coupling to a SMF. The SOA and EAM sections are 600 and 150μm long, respectively, with a 50μm etched electrical isolation region between them.

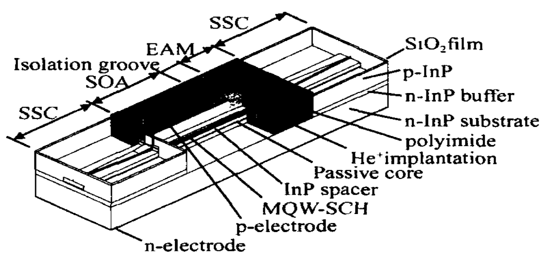

Fig. 1　Schematic diagram of the device

The device is fabricated using only a three-step lower-pressure metal-organic vapor phase epitaxial (LP-MOVPE) process. For the first epitaxial growth, an InP buffer, a 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 SOA region. The multi-quantum well and separate confinement heterojunction (MQW-SCH) stack and 150nm undoped InP implant buffer layer are grown next. The MQW structure consists of ten strained InGaAsP quantum wells and nine lattice-matched InGaAsP barriers. The thickness and bandgap wavelength of SCH layers is about 100nm and 1.2μm. The SAG process creates a bandgap difference between the modulator and the SOA of 75nm, as measured with micro-region photoluminescence at room temperature (for details see Fig. 2). After removing the SiO_2 pads, the SOA/EAM section is encapsulated by a 400nm-thick SiO_2 layer and then the QWI process is carried out on the SSC region. As a result, the peak bandgap wavelength in the SSC region is blue-shifted from 1500 to 1400nm. Then, the SiO_2 1ayer and the undoped InP buffer layer are removed by wet etching and the tapered MQW-SCH core in the SSC regions are formed using a taper-patterned photo-resist mask and selective etching. A sharp taper tip less than 0.4μm at the SSC section is easily achieved by normal photolithography combined with an undercut etching. Thus, there is no need of using an expensive and time-consuming e-beam lithography. A

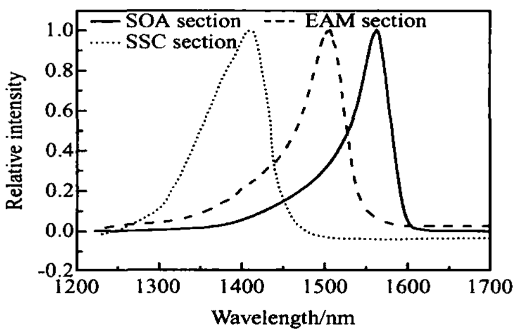

Fig. 2 PL spectra of the SOA, EAM, and SSC regions

thin p-InP cladding layer, 1.2Q etch stop layer, p-InP over-cladding, and an InGaAs cap layer are then grown successively in the third growth step. A double ridge waveguide of the SOA/EAM sections is formed by the conventional process. The width of the upper and lower SOA/EAM mesas are 3μm and 8μm, respectively. The electrically isolated groove between the SOA and EAM sections is formed by etching away the InGaAs cap layer and He^+ ion implantation on it. The InGaAs cap layer in the SSC region is entirely etched away to eliminate excess light absorption (lattice matched InGaAs has an absorption wavelength of 1.67μm). A SiO_2 dielectric layer is then deposited on the wafer. After the waveguide for the SOA/EAM is buried in polyimide, electrodes of SOA/EAM sections and TiO_2/SiO_2 antireflection films on the input and output facets are formed.

3 Device performances

Spectra of the TE and TM amplified spontaneous emission of the amplifier at 100mA bias current and zero bias voltage on the modulators are shown in Fig. 3. Less than 1.2dB polarization sensitivity is maintained over 200nm (1450～1650nm).

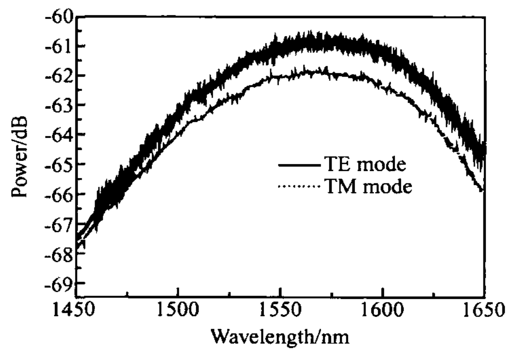

Fig. 3 ASE spectra measured with 100mA injection current to the SOA and 0V voltage to the EAM

Figure 4 shows the far field pattern observed from the SSC facet. It can be seen that the fundamental transverse mode is realized and that the far field pattern of the device can not be affected by adding SSC. The side lobe at an angle of 10° in a horizontal FFP is caused by the reflected light from the submount. The divergence angles of 7.3°×18.0° from the SSC facet are far smaller than those of 30°×49° from the EAM facet without SSC. The coupling loss of the device from the SSC facet to the cleaved SMF is about 3dB and the 1dB align tolerance between them is about ±3.1μm (horizontal) ×(±2.60)μm (vertical). However, for the EAM facet without SSC, the coupling loss and the 1dB align tolerance is about 9dB and ±2.0μm (horizontal) ×(±1.7)μm (vertical), respectively.

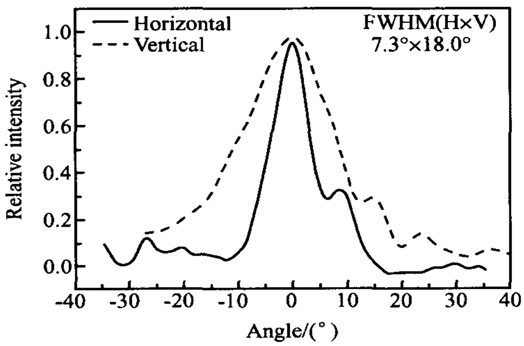

Fig. 4　Far-field pattern from SSC facet

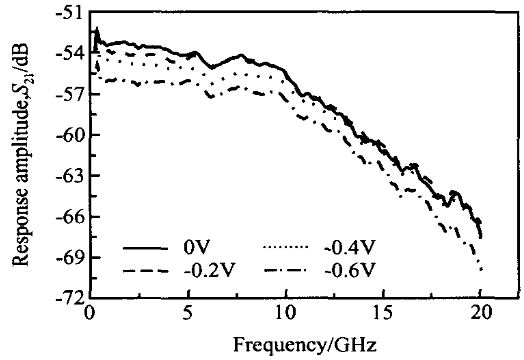

Fig. 6　Small-signal response curves of EAM at different DC biases

Figure 5 shows the spectral dependence of the fiber to fiber gain in the SOA active region at - 13dBm incident optical power, 100mA bias SOA current and zero bias voltage on the modulator. The spectral range is larger than 40nm while the gain change from fiber to fiber is less than 3dB. The device can be worked at loss-less operation from a 1550 to 1600nm wavelength range when both the gain peak of the SOA and the absorption edge of the EAM and SSC have been optimized. These results also come from the high coupling efficiency to an SMF due to the introduction of SSC at the input and output end.

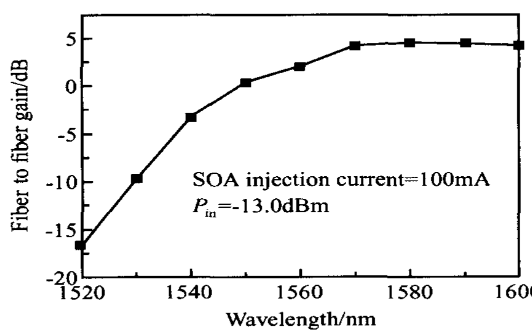

Fig. 5　Optical gain as a function of injected light wavelength

The small-signal response (S_{21}) of the device is measured. Figure 6 shows a plot of the signal modulation at different EAM biases. A 3dB bandwidth of more than 10GHz at EAM bias voltages from 0V to - 0.6V is achieved.

Figure 7 shows the statically extinction ratio (ER) versus EAM bias at 1580 and 1600nm with a 100mA injection current into the SOA section of the device. A high ER of 25dB can be achieved at a bias of - 3.5V for the 1600nm wavelength. At a wavelength of 1580nm, a high ER of 20dB is also obtained at a lower bias of - 2.5V.

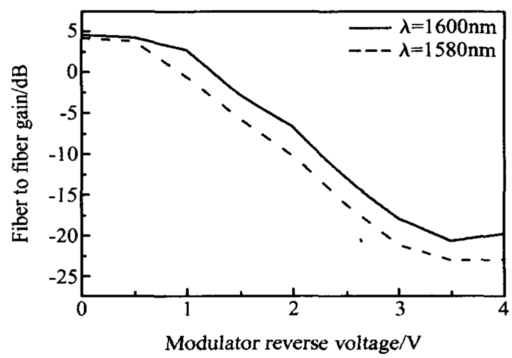

Fig. 7　DC extinction characteristics for electroabsorption modulator

4　Summary

A SOA and EAM monolithically integrated with a novel dual-core SSC is designed and fabricated by means of SAG, QWI, and ATG technologies. The output beam divergence angles are as small as 7.3°×18.0° in the horizontal and vertical directions, respectively. High coupling efficiency with a cleaved SMF (3.0dB loss) and a 1dB alignment tolerance better than ±3.1μm (horizontal) × ±2.60μm (vertical) are realized. A loss-less operation at 1550～1600nm is achieved with a high static ER of 25dB. The 3dB bandwidth of the device is more than 10 GHz with a wide range of incident optical power from - 13dBm to + 8dBm. Simple fabrication procedure and excellent performance make the device suitable for mass-production and a cost-effective device for advanced WDM or OTDM systems.

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电吸收调制器与半导体光放大器和双波导模斑转换器的单片集成*

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摘要: 采用选择区域生长、量子阱混杂和非对称双波导技术制作了电吸收调制器与半导体光放大器和双波导模斑转换器的单片集成器件. 器件在波长 1.55～1.60μm 范围内, 3dB 带宽大于 10 GHz, 直流消光比为 25dB, 插入损耗小于 0dB, 远场发散角为 7.3°×18.0°, 与单模光纤的耦合效率达 3.0dB.

关键词: 半导体光放大器; 电吸收调制器; 模斑转换器; 选择区域生长; 量子阱混杂; 非对称双波导

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