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A Wavelength Tunable DBR Laser Integrated with an Electro-Absorption Modulator by a Combined Method of SAG and QWI*

Zhang Jing, Li Baoxia, Zhao Lingjuan, Wang Baojun, Zhou Fan, Zhu Hongliang, Bian Jing, and Wang Wei

(National Research Center for Optoelectronics Technology, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China)

Abstract: We report a wavelength tunable electro-absorption modulated DBR laser based on a combined method of SAG and QWI. The threshold current is 37mA and the output power at 100mA gain current is 3.5mW. When coupled to a single-mode fiber with a coupling efficiency of 15%, more than a 20dB extinction ratio is observed over the change of EAM bias from 0 to -2V. The 4.4nm continuous wavelength tuning range covers 6 channels on a 100GHz grid for WDM telecommunications.

Key words: tunable lasers; distributed Bragg reflector lasers; electroabsorption modulator; quantum-well intermixing; selective area growth

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1 Introduction

Wavelength tunable electro-absorption modulated DBR lasers (TEML) are very attractive components. They can be used as highly reliable, compact, and low cost wavelength tunable sources in long haul WDM fiber optic communication systems. The key issue for the fabrication of monolithic photonic integrated circuits is the combination of different functional sections (active or passive) on a single epitaxial wafer, which requires the definition of sections with different bandgap wavelengths. In the case of TEML, three different bandgap wavelengths are needed: one for the gain section, one for the modulator section, and one for the grating and phase section, with a relation of $\lambda_{gain} > \lambda_{modulator} > \lambda_{grating}$. To integrate different materials on the same wafer, the most popular methods are selective area growth (SAG)[1], butt-joint[2], single-mode vertical integration (SMVI)[3], and quantum-well intermixing (QWI)[4]. Among them, butt-joint coupling needs overcritical etching and re-growth steps, while SMVI needs special waveguide design, longer chip size, and a rigorous etching process. Both of them require complex fabrication techniques and efficient optical coupling between different sections is hard to realize.

SAG allows simultaneous epitaxy on a patterned substrate with different growth rates and

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Zhang Jing male, was born in 1975, PhD. His research interest is in InP-based photonic integrated circuits.

Li Baoxia female, was born in 1977, PhD candidate. Her research interest is in InP-based photonic integrated circuits, especially the monolithic of DFB laser and high speed EA modulator.

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results in the growth of quantum wells with different thicknesses, therefore defines of sections with different bandgap wavelengths. By locally introducing a different SiO_2 pattern, more than three bandgap wavelengths can be realized in the same SAG growth, which is sufficient for the fabrication of TEML. The main drawback of SAG is that there exists a transition area between different sections with a typical length of several tens of micrometres. The transition area has gradually changed bandgap wavelengths, thus the optical absorption loss in the transition area may be high.

QWI relies on selective partial material interdiffusion between the well and barrier induced by impurities or vacancies during a post-growth anneal process, which results in a change of QW shape and transition energies. QWI has high space resolution[5] (several micrometres) and an abrupt bandgap wavelength change between different sections. A schematic view of SAG and QWI process is shown in Fig. 1.

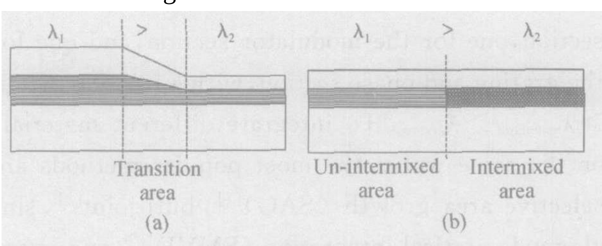

Fig. 1 Schematic view of SAG (a) and QWI (b)

Although a SAG method can be used to fabricate TEML, we adopt a combined process of SAG and QWI in this paper. There are two benefits of the method compared with the former one: (1) We can adopt the same quantum-well structure and growth condition which we used to fabricate the integrated DFB laser and EA modulator before[6], thus make the fabrication process easier; (2) The QWI process results in an abrupt bandgap wavelength change between different sections, thus reducing absorption loss in the transition area. The QWI process has been well established in our group[7].

2 Device fabrication

A schematic illustration of the tunable EA-DBR chip is shown in Fig. 2. The device consists of five separate sections: a 250μm rear grating; a 300μm gain section; a 100μm phase section; a 50μm front grating; and a 150μm EA modulator. Trenched isolation regions separating each of the sections are all 50μm long.

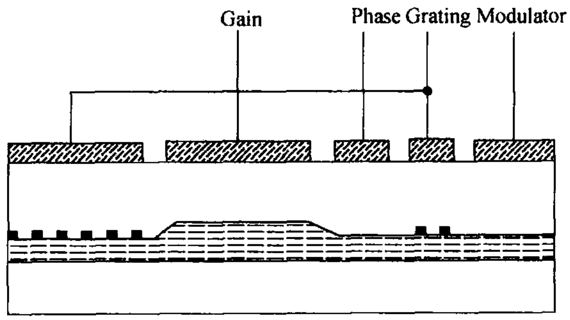

Fig. 2 Schematic cross section of the EA-modulated tunable DBR laser

First, we deposited a SiO_2 dielectric film with typical thickness of 150nm by PECVD on a (100)-oriented n-InP substrate. Then, stripe patterns were defined in the SiO_2 mask by conventional photolithography and chemical etching at gain sections. The strips were formed along the [110] direction. Both the mask strip width and the open stripe width are 15μm. A n-InP buffer layer, MQW active waveguide layers, and an i-InP implant buffer layer were then grown in turn by low pressure MOCVD on this patterned substrate. The InGaAsP MQWs consisted of 7 periods 6nm compressively strained (0.4%) wells, separated by 9nm tensile-strained (-0.2%) barriers, which was sandwiched between 100nm lower and upper cladding layers. The as-grown MQWs had a PL peak wavelength of 1.560μm at gain section and that of 1.502μm at other sections. Then P^+ ions were implanted into the surface of the whole wafer except gain and modulator sections with an ion energy of 50keV and dose of $5\times10^{13}cm^{-3}$. After re-depositing a fresh SiO_2 layer on the whole wafer, a thermal anneal of 2min at 700 ℃ was performed to induce the QWI process. As a result of QWI, a near 100nm wavelength blue-shift occurred at P^+ ions implanted sections. Detailed wavelength change of different sections after the whole process is shown in Fig. 3.

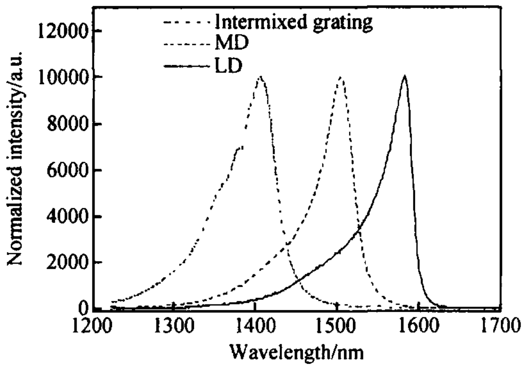

Fig. 3　PL spectra of different sections after thermal anneal at 700 ℃ for 2min

By a combined method of SAG and QWI, we had integrated three materials of different wavelengths in the same epi-wafer to meet the need of TEML (1560nm for gain section of LD, 1502nm for modulator, and 1406nm for grating/phase), and there was no distinct change of intensity and FWHM of PL at non P^+ implanted sections after thermal anneal, which means that QWI process does not deteriorate the MQW quality of the regions which are not to be intermixed. The grating, which was localized at the mirror sections, was realized by convenient holographic lithography followed by dry and wet etching. The reflectivity of the rear- and front- grating are over 80 % and 10 % respectively. The grating coupling coefficient k is about $70cm^{-1}$. Finally, a p-InP layer and a p^+-InGaAs contact layer were grown over the whole wafer.

A standard 2μm-wide single-mode ridge waveguide was etched to 100nm above the waveguide core. Electrical isolation between the different sections was accomplished by a selective wet etching off the InGaAs contact layer and performing a deep He^+ implant. To reduce the junction capacitance of the modulator, a 8μm deep-ridge was etched down over MQW active layers. Passivation of ridge sidewall was accomplished through a 400nm-thick SiO_2 layer. A standard Ti-Pt-Au metal was sputtered and a p-electrode pattern was formed by using a lift-off approach. For further decreasing parasitic capacitance of the modulator, a 3μm-thick polyimide layer was performed under the modulator bonding pad to serve as a low-k dielectric. Then, the wafer was made thin and Au-Ge-Ni contact was performed on the n-side. Finally, after being cleaved to bars, AR coating was formed on the modulator output facet.

3　Device performances

The light output power versus gain section current (P-I) performance at various bias voltages of the modulator is shown in Fig. 4, which is tested at room temperature using an integral sphere. The TEML has a threshold current I_{th} of 37mA. The 50μm-long isolation trench between different laser sections should be further shortened to reduce internal optical loss in the laser cavity, and thus reduce I_{th}. There was no observable change in I_{th} nor in the wavelength of the output light over the entire range of the modulator bias voltage, which indicates sufficient electrical isolation of the laser and modulator sections. With the modulator in an open circuit state, the CW output power is 3.5mW at I_{gain} = 100mA, $I_{grating}$ = 0mA, and I_{phase} = 0mA.

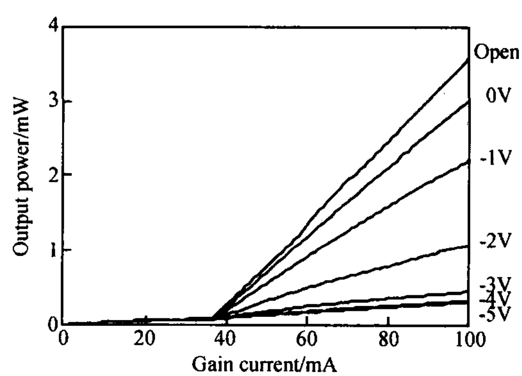

Fig. 4　P-I characteristics of the TEML at different modulator bias voltages

The output power is coupled into a single-mode fiber with a coupling efficiency of 15 %, and the DC extinction characteristic is presented in Fig. 5 under the conditions of I_{gain} = 100mA, $I_{grating}$ = 0mA, and I_{phase} = 0mA. More than 20dB extinction ratio was demonstrated with modulator reverse bias increasing from 0 to 2V. We find a great increase in the extinction ratio compared with the measured results by the integral sphere, which is due to the fact that some un-modulated scattering light is collected by the integral sphere and deteriorates the measured extinction ratio.

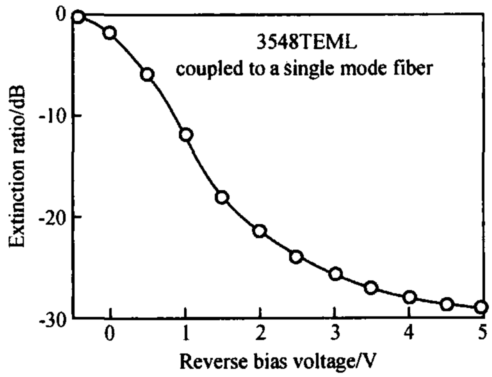

Fig. 5 Extinction ratio of TEML coupled to a single mode fiber measured by integral sphere

By changing the injection current in the grating and phase section, we measure the tuning characteristics of the TEML. The optical spectrum has a 4.4nm tuning range, which covers 6 channels on the 100GHz WDM grid: the channel wavelengths are 1554.94, 1554.13, 1553.33, 1552.52, 1551.72, and 1550.92nm, respectively. The tuning characteristic is demonstrated in Table 1, and the spectra of all the 6 WDM channels are shown in Fig. 6. DC side-mode suppression ratio (SMSR) keeps greater than 35dB over the total tuning range. We observe no significant variation in the extinction ratio when

Table 1 Tuning characteristic of the TEML

$I_{grating}$/ mA	I_{phase}/ mA	Peak wavelength/ nm
0	6	1554.94
4	18	1554.13
7	3	1553.33
18	6	1552.52
30	12	1551.72
42	9	1550.92

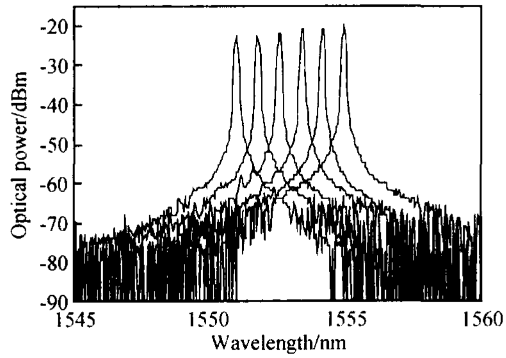

Fig. 6 Tuning spectra for TEML showing 6 channels spaced at 100GHz WDM grid over a 4.4nm tuning range The SMSR is greater than 35dB over the entire tuning range

the laser wavelength is tuned to a given channel, which is due to the small wavelength tuning range.

The capacitance of the modulator is measured to be 0.88pF under - 2V bias voltage and 1MHz frequency, and dynamic characteristics of the device will be further investigated.

4 Conclusion

A combined method of SAG and QWI was successfully utilized to realize a wavelength tunable electro-absorption modulated DBR laser for the first time. Without extra epitaxial regrowth, three functional sections with different wavelengths are integrated on the same wafer. This approach simplifies the fabrication process without significantly compromising the performances of the device, and therefore is a promising technique in the fabrication of photonic integrated circuits.

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基于 SAG 和 QWI 结合技术的电吸收调制器与可调谐 DBR 激光器的单片集成*

张　靖　李宝霞　赵玲娟　王保军　周　帆　朱洪亮　边　静　王　圩

(中国科学院半导体研究所 光电子技术国家研究中心, 北京　100083)

摘要: 报道了基于选择区域生长和量子阱混杂结合技术的电吸收调制器与可调谐 DBR 激光器的单片集成. 集成器件显示出了良好的静态特性: 阈值电流为 37mA; 100mA 激光器增益区偏置电流下, 直流输出功率为 3.5mW; 当使用单模光纤耦合(耦合效率 15%), 调制器偏压在 0～-2V 之间时, 静态消光比大于 20dB; 波长调谐范围为 4.4nm, 覆盖了 6 个 100GHz 间隔的 WDM 信道.

关键词: 可调谐激光器; 分布 Bragg 反射激光器; 电吸收调制器; 量子阱混杂; 选择区域生长

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张　靖　男, 1975 年出生, 博士, 主要从事 InP 基光子集成回路研究.

李宝霞　女, 1977 年出生, 博士研究生, 主要从事 InP 基光子集成回路, 特别是 DFB 激光器和 EA 调制器单片集成的研究.

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