**1.55 µm high speed low chirp electroabsorption modulated laser arrays based on SAG scheme**

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**Abstract:** We demonstrate a cost-effective 1.55 µm low chirp 4 × 25 Gbit/s electroabsorption modulated laser (EML) array with 0.8 nm channel spacing by varying ridge width of the lasers and using selective area growth (SAG) integration scheme. The devices for all the 4 channels within the EML array show uniform threshold currents around 18 mA and high SMSRs over 45 dB. The output optical power of each channel is about 9 mW at an injection current of 100 mA. The typical chirp value of single EML measured by a fiber resonance method varied from 2.2 to 2.4 as the bias voltage was increased from 0 V to 2.5 V. These results show that the EML array is a suitable light source for 100 Gbit/s optical transmissions.

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**References and links**


1. Introduction

To cope with the demand for huge data capabilities in Internet and associated data-driven applications, 100-Gb/s transmission technology has been widely considered as a strong candidate for next-generation terabit per second communication networks [1]. The Electroabsorption Modulated Laser (EML) has attracted much attention due to its compactness, low packaging cost, low driving voltage and high stability [2–7]. Monolithically integrated EML arrays are promising light sources for modern reconfigurable dense wavelength division multiplexing (DWDM) systems. The devices can potentially reduce optical network costs with simplified optical alignment and packaging processes. Compared with the monolithically integrated distributed feedback (DFB) laser arrays and an electroabsorption modulator (EAM) which operates as the wavelength selectable light sources [8], the EML arrays can handle much higher data capabilities and the device performance of different channels in EML arrays can be optimized separately. There have been several reports on EML arrays that operate more than 40 Gbit/s over the past years. Compact monolithically integrated light sources based on 1.310 μm 4 × 25 Gbit/s and 4 × 40 Gbit/s electroabsorption modulated DFB laser array were demonstrated for future long distance data communication systems, respectively [9–11]. A 4 × 1 optical multiplexer was used to reduce the chip size. A 1.55 μm 4 × 10 Gbit/s electroabsorption modulated distributed Bragg reflector (DBR) laser array was also proposed for better control of the output wavelength due to the inherent wavelength tunability of DBR laser [12,13].

Although much progress is made for integrated light sources as mentioned above, it is expected that integrated light sources will be cost-effective and they will demonstrate improved performance of both the laser and the modulator simultaneously with relative simple fabrication processes for practical applications. To fabricate EML arrays, one of the key issues is that different wavelength channel have to be defined side by side on one chip and the lasing wavelength between neighboring channels must have a uniform wavelength space. Up to now, electron-beam lithography (EBL) is the most widely used techniques to fabricate gratings with different periods [9–11]. However, drawbacks such as high costs, time consumption, low yields, and complex manufacture processes make this method not the best choice for mass production. As shown in earlier reports [14], the variation in the ridge width would lead to a slight difference in the effective index and then in the lasing wavelength. And this method was used to fabricate multi-wavelength laser arrays with the same grating period [15,16]. Such width-varying DFB waveguides can be made by standard photolithography and holographic lithography.

Another key issue is the wavelength compatibility between the DFB and the EAM. The DFB lasing wavelength is longer than the absorption-peak wavelength of the EAM. The wavelength detuning between the DFB lasing wavelength and the EAM absorption-peak wavelength can greatly affect the devices performances such as extinction ratio, output power and 3dB bandwidth. Among the many ways of laser-modulator monolithic integration
explored [2–13, 17,18], selective area growth (SAG) has large degree of freedom in bandgap energy control and almost 100% optical coupling achievable between the components. This method allows definition of different regions of MQW bandgaps on a single masked substrate with a one-step growth process. Unlike the butt–joint integration scheme, no partial removal of the active region by selective etching and no different active material by regrowth are necessary for the SAG method. Thus, the fabrication complexity of the EMLs is significantly reduced by using SAG and no postgrowth annealing such as quantum-well intermixing is required. In this work, selective area growth (SAG) is employed to grow an active layer in the regions of the laser and the modulator. The ridge width varying techniques are used to monolithically integrate a 4 × 25 Gbit/s EML array. As a result, the fabrication process of the integrated device is significantly simplified. Our method has great potential for the fabrication of low-cost, high quality integrated multi-wavelength laser arrays.

2. Device design and fabrication

Each EML of the array is composed of a 250 µm long DFB laser and a 170 µm long EAM. Different active regions of laser and EAM at 1552 nm and 1495 nm respectively, have been obtained by the SAG method. The laser array is designed to have a frequency spacing of 100 GHz (0.8 nm) which is obtained by slightly changing the ridge waveguide width according to:

$$2n_{\text{eff}}\lambda = m\lambda_b$$

Where the $\lambda$ is the grating period, $\lambda_b$ is the Bragg wavelength determined by the hologram lithography, $n_{\text{eff}}$ is the effective refractive index in waveguide structure and $m$ is grating order which is 1 here for the first order grating. The EML arrays have a typically 2.0 to 3.5 µm-wide ridge waveguide structures to achieve transverse fundamental mode operation. The transverse fundamental mode operation is necessary for EML with single longitudinal mode output because high order transverse modes lead to power kinks, side-mode-suppression reduction or multimode lasing. The effective refractive index of the ridge waveguide as a function of the waveguide width was calculated by using beam propagation method (BPM). For all of the four-channel EML in the array, waveguide width are designed as 2 µm, 2.35 µm, 2.6 µm and 3.1 µm, which corresponds to the calculated effective index of 3.21, 3.2116, 3.2133 and 3.2149, respectively.

The designed EML array was fabricated using the similar process in [2]. Device fabrication started with deposition of 200 nm thick SiO$_2$ dielectric films on the S-doped (100) InP substrates by plasma-enhanced chemical vapor deposition (PECVD). Masks were patterned along the [011] direction by conventional photolithography. Then, an n-InP buffer layer and an eight-pair InGaAsP/InGaAsP MQWs structure were selectively grown on the patterned substrates by ultra-low-pressure MOCVD (30 mbar, 655°C). The MQWs consist of undoped 8-nm-thick 0.7% compressive strain InGaAsP wells separated by 9-nm-thick 0.3% tensile strain In$_{0.85}$Ga$_{0.15}$As$_{0.42}$P$_{0.58}$ barriers, sandwiched between 100-nm-thick lattice-matched In$_{0.75}$Ga$_{0.22}$As$_{0.47}$P$_{0.53}$ optical confinement layers. It is well known that the principal mechanism of selectively grown MOCVD lies in the lateral gas phase diffusion of group-III precursors. At ultra-low pressures, the reagent particles can easily diffuse out of the stagnation gas phase layer. The measured growth enhancement rate between the stripes is 20% which fits well with the lateral gas phase diffusion model. A first-order grating with period of 241.7 nm is partially formed on the laser section by conventional holographic exposure followed by chemical etching. The exposure and dry-etching processes were controlled to achieve a grating duty factor of approximately 50% for an optimum coupling coefficient. To complete the epitaxial structure, a p-type InP cladding layer and p + InGaAs contact layer were successively grown.

To ensure a small series resistance of the DFB laser and a low capacitance of the EAM, a single reverse-mesa-ridge structure was formed by conventional photolithographic technology and etching along the [011] direction. RIE was first employed to remove the p + InGaAs contact layer during the ridge etching. After that, the p-type InP cladding layer was etched by
using selective wet chemical etching in HCl:H₂O solution. The etching processes were controlled to achieve the low loss reverse-mesa-ridge. The EA modulator section was further processed into deep mesa ridge waveguide structure by the second RIE step to reduce the junction capacitance of the device. Electrical isolation between the laser and the modulator were realized by forming 50-μm-wide trench between them and adopting He⁺ implantation in the trench. Three steps of He⁺ implantation were used for a flat ion distribution with doses of $1 \times 10^{14}$, $8 \times 10^{13}$, $5 \times 10^{13}$ cm⁻² and at energies of 180kev, 100kev, 80kev respectively. An isolation resistance greater than 100 kΩ was obtained. BCB was used under the bonding pad to reduce the parasitic electrode pad capacitance of EAM. The ridge waveguide was well protected and passivated. Thus low capacitance of the modulator and low leakage currents were obtained. Then, patterned Ti/Au p-electrode was formed on top of the planarized wafer. Au/Ge/Ni n-electrode was evaporated onto the backside of the device after thinning the wafer down to about 100μm. Finally, the wafer was cleaved into device chips, and the facet of the EA modulator and DFB laser were antireflection (AR) and high reflection (HR) coated with dielectric layers deposited by PECVD, respectively. A 40-GHz vector network analyzer and a calibrated receiver were applied for a high-speed measurement.

3. Characteristics of the device

The device was mounted on a copper submount using an optimized Au₈₀Sn₂₀ solder. The copper submount was placed on a thermoelectric cooler (TEC) to control the chip temperature under continuous-wave (CW) operation. During the measurement, the EMLs were discrete operated. The serial resistance of the fabricated lasers is $4 \pm 0.1$ Ω. Figure 1 shows the measured light output power versus injection current curve of a typical chip of EML array at the temperature of 25°C. A threshold current as low as 18 mA and an output power of about 9mW at 100mA was achieved for each EML channel.

![Fig. 1. Typical light output power versus current curve of a typical chip of EML array at the temperature of 25°C under CW condition.](image)

The output light from the EML array was collected by a lensed single mode fibre and coupled to an optical spectrum analyzer (OSA) for spectrum analyse. Figure 2 shows the recorded spectra for all 4 channel lasers at the injection current of around 65 mA. The lasing wavelengths were around 1551.80 nm, 1552.56 nm, 1553.28 nm, and 1554.04 nm, which had a slight shift of around ± 0.1 nm from the design due to lithography resolutions. The measured single-mode suppression ratios (SMSRs) are larger than 40 dB and the average value is 45 dB, which exhibits good single longitudinal mode property in the DFB laser array. The measured
lasing wavelengths appear to have good linearity. After linear fitting, the residual wavelength changes only from $-0.004$ to $0.012$ nm, this is relatively quite small. Supposing that the gratings are fabricated by other advanced fabrication methods such as EBL, the deviation of period must be controlled within a very small value of $0.124$ nm, corresponding to the tolerance of $0.8$ nm. As we know, it is quite challenge to obtain space of grating pitches less than $1$nm with typical EBL. We also measure the output optical spectrum of the EML under different operation injection current. The wavelength shift is about $0.012$ nm/mA. Thus, the EML array can be finely tuned by changing the injection current of each channels and the required injection current range is about $10$ mA to make the lasing wavelengths exactly linear.

The divergence angles from the EAM output are $40.2^\circ \times 34.6^\circ$ in the vertical and horizontal, respectively; the coupling efficiency to single mode fiber reached $42\%$ in the experiment. In Fig. 3, the dc extinction ratio of all the four EML channels measured using an integrating sphere is plotted as a function of the reverse bias applied to the EAM. The extinction ratio at $5$V reverse bias is estimated to be approximately $15$ dB. When coupled to single mode fiber the dc extinction ratio at $5$V reverse bias is more than $35$dB. By adopting a deep ridge waveguide and planar electrode structures combined with buried BCB, the capacitance of the EAM is reduced to $0.22$ pF. The measured relative E/O response of a typical EML channel
(channel 2) is shown in Fig. 4, which has been calibrated to account for the frequency response of the photo detector and high frequency probe. The measured 3dB bandwidth is more than 18.5 GHz (~24 GHz by fitting the experimental result) for all the four channels, which are sufficiently large for 25 Gbit/s NRZ signal operation. The intrinsic bandwidth of the EML will be larger if the resonance is removed by optimizing the design of the submount.

Wavelength chirping which is defined as the ratio of the increments of the real and imaginary parts of the EAM complex refractive index is important to the transmission characteristics of an EAM. The wavelength chirping is estimated from the small signal parameter measurements using a fiber resonance method proposed by Devaux et al. [19]. Figure 5 shows the reverse bias voltage dependence of the $\alpha$ parameter for EML channel 2. The $\alpha$ parameter varies from 2.2 to -4, as the reverse bias voltage increases from 0V to 2.5V. A zero chirp parameter was achieved at a bias voltage of 1.58 V. The transfer characteristic of the device offers potential for getting a low dispersion penalty.
4. Discussions and conclusions

A low chirp $4 \times 25$ Gbit/s EML array with 0.8 nm channel spacing has been fabricated by varying the laser ridge width and SAG. The grating was fabricated only by common holographic exposure and an additional micrometer-level standard photolithography, which results in a low cost. The device shows uniform threshold current around 18 mA and high SMSRs over 45 dB. The optical output power of each channel is about 9 mW at an injection current of 100 mA. The chirp values of the EML chip were measured using a fiber resonance method. The chirp varied from 2.2 to 4 as the bias voltage was increased from 0 V to 2.5 V respectively. The transfer characteristic of the device indicates potential for transmission with a low dispersion penalty. The experiment results show that our technique is a simple and powerful tool for the fabrication of low-cost, high quality multi-wavelength laser arrays.

Acknowledgments

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