Investigation of the Capacitance of Integrated DFB–EAMs with Shared Active Layer for 40 GHz Bandwidth

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Laser-integrated electroabsorption modulators with shared active area are potentially inexpensive high-speed light sources but suffer from certain design drawbacks. It is shown how to increase the cut-off frequency beyond 40 GHz without losing fabrication simplicity.

1. Introduction

![Fig. 1: Integrated DFB–EAM device layout.](image)

Electroabsorption modulators (EAMs) integrated with distributed feedback (DFB) lasers are attractive light sources for modulation speeds up to the 40 Gbit/s regime and beyond. In contrast to other realizations [1], devices with a common active area are of particular interest as their growth and fabrication complexity is comparable to standard DFB lasers. However, the concept of a single grown active area imposes two major challenges on the EAM design: First, the operating wavelength has to be close to the bandgap in order to achieve sufficient gain in the DFB section for low laser threshold currents. Therefore, the residual absorption in the EAM is high and the bias voltage is limited to low values.

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for sufficient output power. Both can result in serious carrier pile-up effects. Second, the DFB grating layer acts as an etch stop layer during the ridge fabrication process in both sections. The spacing between the grating layer and the waveguide is $d_{sp} = 150 \text{ nm}$ to optimize the coupling coefficient in the laser section. The consequence is an unwanted lateral conductance in the EAM section. With decreasing modulation frequency the effective capacitance gets larger and degrades the RF performance (‘field spreading’). After recognizing a poor RF performance of the first generation DFB–EAMs, a model was developed that considers intrinsic and extrinsic device parameters. With this model, the small-signal measurements could be verified and design rules were identified.

2. First Device Generation

The reported investigations were carried out on a monolithically integrated DFB–EAM. The device schematic is displayed in Fig. 1. A detailed report on the fabrication steps is given in [1]. The active area consists of a single grown AlGaInAs double quantum well (QW) stack on n-InP substrate that is able to deliver high gain with forward current injection and high absorption swing with reverse bias voltage at 1308 nm operation wavelength [2]. The intrinsic area is 270 nm thick. A local buried grating is introduced in the 380 \mu m long DFB section. Lateral waveguiding is performed by a 2 \mu m wide ridge on top of a 8 \mu m wide second mesa. The EAM section is 100 \mu m long. The specific resistance of the p-region is $\rho_p = 0.25 \Omega \text{cm}$. The device showed a threshold current of 18 mA, a maximum output power of 1 mW and an extinction ratio of 10 dB/V in the EAM section.

3. Simulation and Measurement Results

In a well designed EAM, the steady state carrier distribution is reached after a few ps. For the modulation behavior up to 50 GHz, the active area can be modeled as a variable capacitor $C(V_{EAM}, P_{abs})$ depending on the absorbed optical power $P_{abs}$ and the reverse bias $V_{EAM}$. Stationary reverse band diagrams (Fig. 2) were calculated by a 1D drift-diffusion semiconductor simulation [2] that additionally features a carrier generation term, field dependent QW escape time constants and carrier mobilities including saturation velocity. Figure 3 displays the simulated capacitance per area of the active region together with measurement results. Without input light, the capacitance decreases with reverse bias as the space charge region (SCR) increases. With optical input, photo carriers are generated and separated by the electrical field. Similar to a dielectric in a capacitor they create a screening field that weakens the initial field and increases the capacitance. For low reverse bias voltages and high optical power, the effect escalates as soon as the screening field gets into the order of magnitude of the initial field and carriers do not reach saturation velocity anymore. In the next step, the calculated capacitance is introduced into the equivalent circuit model of Fig. 4 that accounts for field spreading, parasitic pad capacitance and the electrical measurement setup. Figure 5 shows simulated and measured electrical small-signal graphs of the EAM traveling wave contact which are in excellent agreement. While
Fig. 2: Band structure of EAM at $V_{\text{EAM}} = 0$ V and $P_{\text{abs}} = 10$ mW.

Fig. 3: Measured and simulated capacitance of the pin-structure.

the bandwidth is almost independent of the optical power at $-2$ V EAM bias, it is cut in half at 0 V bias and 60 mA laser current due to carrier pile-up. All graphs show a major decrease in response below 10 GHz caused by field spreading at low frequencies. With the first layout, the bandwidth is limited to approximately 18 GHz.

4. Redesign

For the redesign, three major changes were introduced: First, the structure was grown on semi-insulating substrate reducing the pad capacitance. Second, the 2 $\mu$m wide EAM ridge was etched through the active region with a nitrogen-based dry-etching process.

Fig. 4: Equivalent circuit model of the EAM.

Fig. 5: Measured and simulated electrical transmission $s_{21}$. 
Third, the detuning of the DFB wavelength to the QW photoluminescence was increased, thus sacrificing laser threshold for less residual absorption at reverse EAM bias voltage. The corresponding small-signal predictions are shown in Fig. 6. Modulation bandwidths of 40 GHz are accessible with reasonable output power and laser threshold. In fact, first experimental results have shown 41 GHz optical bandwidth, 31 mA laser threshold current and 1 mW optical output power.

5. Conclusion

We have developed a simulation tool to study the small-signal performance of EAMs taking into account intrinsic carrier phenomena as well as extrinsic parasitics. Simulation results are in excellent agreement with measured data and allow for detailed insight in carrier pile-up and field spreading related effects. By design optimization, the 3 dB bandwidth of the device was boosted from 18 to 41 GHz. To our knowledge, this is the first integrated DFB–EAM at 1300 nm operating wavelength exceeding 40 GHz in bandwidth.

References
