Extremely High-Power Laser-Modulators with Integrated Amplifier Section (EML-SOAs)

H. Debrégeas(1), N-L.Tran(1), N. Dubrovina(1), E.Durán-Valdeiglesias(1) , R.Rosales(2), R.Brenot(3)

(1) Almae Technologies, Route de Nozay, 91460 Marcoussis, France, helene.debregeas@almae-technologies.com
(2) Huawei Technologies, Riesstr. 25, 80992, Munich, Germany
(3) Huawei Technologies, 92100 Boulogne Billancourt, Paris, France

Abstract *We present an EML-SOA targeting highest modulated power. The SOA section is designed to maximise saturation power, in order to reach high power while still operating in SOA linear regime. We demonstrate for 1342 nm 50 GPON a record 15.2 dBm modulated power.*

Introduction

Some communication networks do not include optical amplification, either because they are in the O-band where on-line Erbium Doped Fiber Amplifiers (EDFAs) are not available, or in access Passive Optical Networks (PONs). The transmission distance is then limited mainly by the optical budget, i.e. by the photodiode sensitivity, and by the modulated power emitted by the transmitters.

For example, O-band 400-800 GbEthernet transmissions are based on 100 Gb/s transmitters per channel in 4-level modulation (PAM4). The propagation distance is in general limited to 10 km or exceptionally 40km, due to high fiber losses (~0.34 dB/km).

For PON access networks, several wavelength ranges and data rates are under development. At 1577 nm 10 Gb/s for COMBO-PON requires 5 dBm modulated power in module, i.e. at least 10 dBm modulated power from the chip facet. For the highest data rates, 25G-PON at 1358 nm and 50G-PON at 1342 nm, the required facet modulated powers are today about 13 dBm, and specifications keep increasing.

Directly modulated lasers (DMLs) can achieve high powers, and their bandwidth has been improved to reach 100 Gb/s modulation [1]. However, they are limited in extinction ratio (5-6 dB), and in transmission distance due to their positive chirp, in particular for all applications where the chromatic dispersion of the fibres is not zero (C, L, or high part of O-band).

Therefore, Externally Modulated Lasers (EMLs) with a Distributed FeedBack (DFB) laser section and an electro-absorption modulator are preferred for many applications, but their optical power is limited firstly by modulator absorption, and secondly by modulator saturation due to piling-up of photogenerated holes which screen the applied electrical field. By increasing the laser-modulator detuning to limit modulator insertion loss and operate under high electric field, we have demonstrated a facet modulated power of 13 dBm for 50G-PON 1342 nm applications [2]. However, this is at the cost of a higher peak-to-peak modulation voltage Vpp of the modulator around 2.5 V.

A simultaneous modulation of the laser and modulator sections has demonstrated increased power [3], but it increases cost and complexity with two simultaneous RF sources.

Another approach is the monolithic integration of a Semiconductor Optical Amplifier (SOA) section at the output of the EML (EML-SOA) to boost the output power. The concept was introduced in 2003 [4], and since then it has been widely studied and developed by several groups, for different data rates (up to 100Gb/s PAM4) and different wavelength ranges (O, C, L bands) [5-7]. But the maximum power is limited by the saturation power of the SOA, and to our knowledge the record value obtained is limited to 10 dBm fibre coupled modulated power.

In this paper, we present an EML-SOA where the structure is optimised not to optimise the laser cross-section, but to maximise the saturation power of the SOA. We demonstrate an EML-SOA operating at 1342 nm compatible for 50 Gb/s modulation, with saturation power of 20.8 dBm for 200 mA total injected current, and a facet modulated power of 15.2 dBm (12.8 dBm fibre modulated power) with clear eye diagram.

EML-SOA limitations

The SOA section provides a gain G proportional in dB to its length, which increases the power output of the EML. But the SOA can also be particularly disruptive to the eye pattern as explained below.

The main power limitation of the EML-SOA is the SOA saturation power (Psat). When the power P_{in} injected into the SOA increases, the photon density - especially at the end of the SOA section - becomes too high: the injected carriers are consumed and their density decreases, which reduces the gain. This effect can strongly degrade the eye diagram as illustrated in Fig.1 at data rates of 2.5 and 25 Gb/s, for different laser and SOA currents (I_{laser} and I_{SOA}). At low I_{laser} (70 mA) and I_{SOA} = 60 mA, the eyes are clean (Fig.1ab). But when I_{laser} is increased to 150 mA, a progressive decrease in power is observed at the beginning of bit 1 due to gain saturation, visible in particular at low bit rates because the carrier consumption effect is relatively slow. At 25 Gb/s this effect creates noise on the 1-level (Fig.1cd). If I_{SOA} is further increased to 100 mA, more carriers are injected and the saturation effect is less important (Fig.1ef).

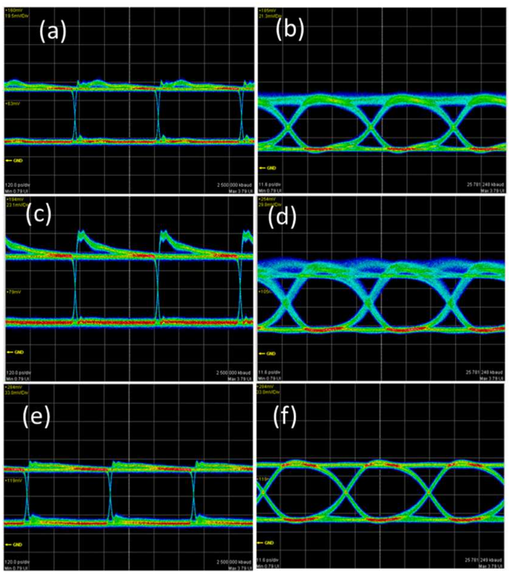

Figure 1: eye diagrams at 2.5 Gb/s (a,c,e) and 25 Gb/s (b,d,f) illustrating SOA saturation effect.
(a-b) I_{laser}=70mA, I_{SOA}=60mA, (c-d) I_{laser}=150mA, I_{SOA}=60mA, (e-f) I_{laser}=150mA, I_{SOA}=100mA

Another risk of EML-SOA comes from the extremely high sensitivity of EML to optical feedback from the front facet, because modulated light excites the laser that oscillates at its characteristic resonant frequency. This effect creates noise especially on the 1-levels. The feedback rate must therefore be maintained below -40 dB (0.01 %) using sophisticated anti-reflection coating. With the SOA section, the optical feedback is way more detrimental because it is amplified twice in the SOA, i.e. by 2 x G. An EML-SOA would thus require an anti-reflection coating of the order of -50dB, which is not industrially feasible.

Another possible limitation is the amplified spontaneous emission (ASE) from the SOA, which also propagates backwards: it is modulated by the modulator section, and excites the resonance of the laser section, similarly to optical feedback. So even in the complete absence of reflection at the output facet, the laser may exhibit optical resonance. This effect seems negligible in the operating range of the SOAs presented here, but it could become non-negligible for long SOA sections and high I_{SOA}.

EML-SOA design and fabrication

To increase the power emitted by the EML-SOA, the main parameter to be optimised is therefore the saturation power of the SOA. It is given by

$$P_{sat} \,\alpha\, \frac{A_{QW}}{\Gamma_{QW}} \frac{\mathrm{h\nu}}{\tau_r \, dg/dn} \qquad (1)$$

where A_{QW} is the area of the quantum wells (waveguide width *x* well thickness), Γ_{QW} is the optical confinement in the wells, $h\nu$ the energy of a photon, τ_r the carrier recombination time, and *dg/dn* the differential gain. Instead of optimising the active structure for the DFB section, we optimised it for the SOA section for highest P_{sat}, notably by reducing the optical confinement Γ_{QW} in quantum wells, and by integrating an InGaAsP cladding under the quantum wells to attract the mode downwards and reduce optical losses in top p-doped InP.

The fabrication of the EML-SOA is identical to that of the EML presented in [2], with the laser structure identical to the SOA section. We use a butt-joint to independently grow the laser and modulator quantum well structures, using InGaAsP materials in Gas Source Molecular Beam Epitaxy (GSMBE). The waveguide is buried in semi-insulating InP, and laterally implanted with H+ ions to limit the modulator capacitance and electrically isolate the different sections.

The component is shown in Fig.2. It operates at 1342 nm, for application in 50 GPON networks. It comprises a 400 µm DFB laser section, a 110 µm modulator to be compatible with 50 Gb/s modulation, and a 250 µm SOA section. To limit the sensitivity to optical feedback, we integrate a window section without optical guidance before the facet, and a 7 ° tilted output waveguide. This combination reduces the optical feedback by a factor of 100 (-20 dB), thus effectively suppressing oscillations while maintaining a standard EML anti-reflection coating.

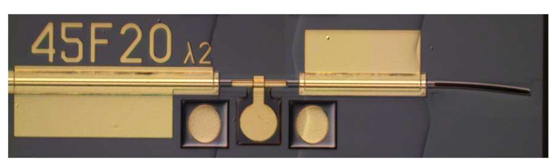

Figure 2: photography of an EML-SOA

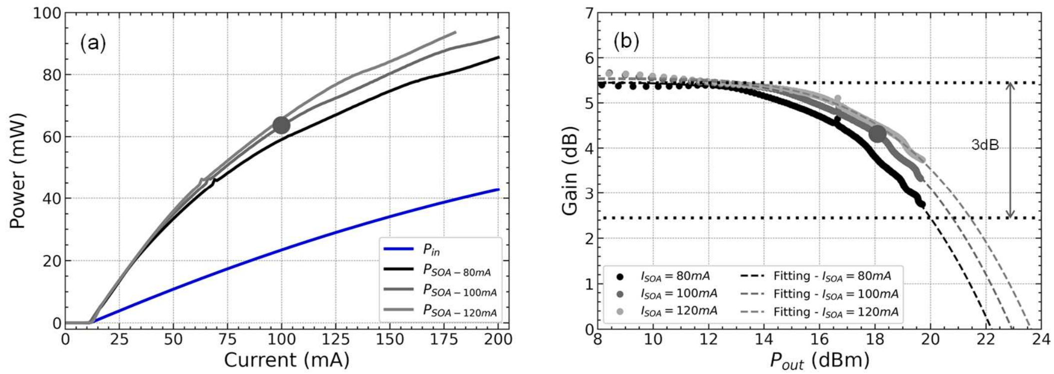

Figure 3: Measurements of gain and saturation power of EML-SOA at 40°C
(a) P_{in} vs I_{laser} via SOA photocurrent measurement, and P_{out} vs I_{laser} for different I_{SOA}.
(b) Extracted SOA gain vs P_{out}, showing P_{sat} values from 20 dBm to 21.3 dBm with I_{SOA} = 80 to 120 mA

EML-SOA performances

P_{sat} measurements are shown in Fig. 3. In Fig. 3a, firstly the power injected by the EML into the SOA (P_{in}) is measured by applying a reverse voltage to the SOA, which then acts as a photodiode, and measuring the photocurrent. Secondly an I_{SOA} current is injected and the output power is measured with a broad detector. Then the SOA gain G can be extracted (Fig. 3b) as a function of the injected power P_{in}, for different values of I_{SOA}. The saturation power P_{sat} is the output power (P_{out}) corresponding to a 3 dB reduction in gain. We obtain a gain of 5.5 dB, and a high P_{sat} of 20 to 21.3 dBm for an I_{SOA} of 80 to 120 mA.

When operating the EML-SOA with I_{laser} = 100 mA and I_{SOA} = 100 mA, which corresponds to the large spots on Fig. 3, P_{out} = 65 mW = 18.1 dBm, which is about 2.7 dB below P_{sat} of 20.8 dBm, such that the SOA operates in a quasi-linear regime. The obtained eye diagram at 25 Gb/s is shown Fig. 4. Thanks to the high SOA saturation power, the coupled average facet modulated power P_{ave_fibre} reaches 12.8 dBm, which corresponds to P_{ave_facet} about 15.2 dBm (2.4 dB coupling losses). The measurements are limited to 25 Gb/s by our equipment, but the EML bandwidth of 35 GHz makes it compatible for 50 Gb/s.

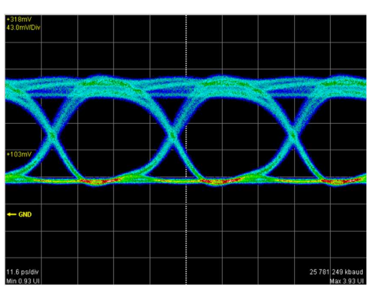

Figure 4: 25 Gb/s eye diagram at 40°C with I_{laser} = I_{SOA} = 100mA. Dynamic Extinction ratio = 5.7 dB, Facet modulated power P_{ave_facet} = 15.2 dBm

The dynamic extinction ratio is limited on these first devices to 5.7 dB due to a high laser-modulator detuning because the wafer was designed for a high power EML, as in [2]. But one great advantage of SOA is the possibility to design the laser and modulator sections for standard output power, that is a moderate laser-modulator detuning for low modulation amplitude V_{pp}, and no risk of modulator saturation. This is of particular interest to reduce modulator power consumption, or for 100 Gb/s PAM4 applications with very low 1.2 V_{pp}.

Another expected advantage of the SOA, that we have not evaluated yet, is the reduction of chirp for longer transmission distance. Indeed, as described in [8,9], saturation of the SOA generates a carrier density reduction, and thereby a negative chirp. By operating our SOA close to saturation, we foresee an improvement of transmission distance, while keeping a clean eye diagram.

Conclusion

We presented an EML-SOA design for very high power, notably for access or long-distance LAN applications. At 1342 nm operation for 50GPON, we have optimised the SOA section to achieve a very high 20.8 dBm P_{sat}, resulting in a record facet modulated power of 15.2 dBm for I_{laser} = I_{SOA} = 100 mA with a clean eye diagram.

This SOA integration allows the constraints on the EML part to be relaxed, in particular for high bit rates, and for low V_{pp}. The impact of the SOA in transmission remains to be tested, but should a priori improve performance thanks to its negative chirp.

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