

Versatile externally modulated lasers technology for multiple telecommunication applications

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Abstract

This paper presents our technological approach for Externally Modulated Lasers (EMLs), based on Semi-Insulating Buried Heterostructure (SIBH) waveguide. We present the main EML design rules and compromises, then apply them to different EMLs aiming at major telecom and datacom applications.

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Abstract—This paper presents our technological approach for Externally Modulated Lasers (EMLs), based on Semi-Insulating Buried Heterostructure (SIBH) waveguide. We use Gas Source Molecular Beam Epitaxy (GSMBE) to grow the Phosphorus-based multi-quantum wells for both laser and modulator sections with butt-joint integration. The same GSMBE grows the p-doped InP claddings with low-diffusion Be dopant, leading to an accurate control of doping profiles, ensuring very steep modulator extinction curves. We present the main EML design rules and compromises, then apply them to different EMLs aiming at major telecom and datacom applications. After presenting characteristics of the standard 10 Gb/s C-band EML, we propose a 10 Gb/s EML at 1577 nm for next generation access networks, with a record high 10.5 dBm facet modulated power. Then we present high-speed EMLs up to 56 GBaud for datacenter interconnections, both in O- and C-band, aiming at very low peak-to-peak modulation voltage (< 1.2 V), high facet modulated power (> 4.4 dBm), and compatible with uncooled operation (20 to 70 °C). These results confirm the efficiency and versatility of this technological platform for EMLs in a broad range of applications.

Keywords—C-band, Electro-Absorption Modulated Laser (EML), O-band, uncooled.

I. INTRODUCTION

WITH the extremely rapid growth of new services, particularly video and 5G, optical networks must evolve rapidly towards higher and higher speeds, and provide solutions adapted to each type of transmission. Long-distance transmissions use optical amplification and aim at the highest spectral density. To achieve this, they adopt a multitude of dense wavelength division multiplexing (DWDM) sources, with complex modulation formats in amplitude, phase and polarization (QPSK, QAM, ...), together with the signal processing to reconstruct the received signal using sophisticated error correction codes. The most common technological approach uses high-power InP continuous lasers, coupled into the photonic on silicon circuits, which allow modulation with complex formats, as well as passive functions such as multiplexing / demultiplexing, splitting... In reception, these complex formats require the use of a laser as a local

oscillator and several photodiodes in order to retrieve the amplitude and phase information of the signal.

For shorter distance transmissions, it is possible to use simple amplitude modulation such as NRZ or PAM4 for example. These formats require less complex components to generate the modulation, and can be detected by simple photodiodes. A first technological approach uses Directly Modulated Lasers (DMLs) where the optical power is varied via the current injected into the laser. This very simple and low-cost approach makes it possible to achieve high output power with low-power consumption. For very short distances of a few meters, e.g. in data centers, the most common solution is Vertical Cavity Emission Lasers (VCSELs) coupled into multimode fibers, which are very low cost to manufacture and package. For slightly longer distances up to 20 km, edge-emitting Distributed Feedback (DFB) lasers coupled into a single-mode fiber are used. An optimized design of the quantum wells using Aluminium-based active material allows these lasers to operate over a very wide temperature range of about 100 degrees (0 to 85°C typically). This uncooled operation, with no Peltier element, further reduces cost and power consumption.

However, the direct modulation of the laser, controlled by the injected electrical current, causes a variation in the density of electrical carriers and photons in the laser cavity. This changes the effective index of the optical mode, thus the emitted wavelength, which becomes different between 0 and 1 (adiabatic chirp). Moreover, these two effects interact and generate an oscillation phenomenon at a resonance frequency of the laser, in the order of a few GHz. An oscillation of the emitted power and wavelength is observed, especially when high modulation amplitudes are sought (extinction ratio > 5 dB). In optical fiber, the different wavelengths propagate at slightly different speeds (chromatic dispersion). The phenomena of adiabatic chirp and relaxation oscillation therefore lead to strong degradation of the signal after propagation in the optical fiber. Therefore, DMLs are generally limited to O-band applications around 1300nm where chromatic dispersion is the lowest, for uncooled applications such as in subscriber access networks to generate uplink signals. In recent years, much work has been done to increase the performance of DMLs, in particular by increasing the resonant frequency of the laser. For example, transmissions at 25 GBaud and even 56 GBaud PAM4 have been successfully demonstrated [1].

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For C-band applications where the chromatic dispersion of the optical fibers is higher, or for most high-speed applications (50 Gb/s and 100 Gb/s), the component used is the Electro-absorption Modulated Lasers (EML). It is deployed in particular for metropolitan area networks in C-band up to 80 km, or in O-band for interconnection between data centers (distances of about 80 km in 4×25 Gb/s, then 4×100 Gb/s PAM4), or within data centers (distances of less than 2 km in 4×100 Gb/s PAM4 modulation, then 800 Gb/s and probably in the future 1.6 Tb/s). The EML consists of a continuously operating DFB laser section monolithically integrated with an Electro-absorption Modulator (EAM) section. The EAM is a transparent section, which becomes absorbing when a reverse voltage is applied. Since the laser cavity emits continuously, there are no adiabatic chirp or relaxation oscillation effects in this case. Only a slight variation in wavelength appears at the transition between 0 and 1, when the voltage in the modulator changes, thus changing the phase of the transmitted wave (transient chirp). The optical amplitude and frequency characteristics shown in Fig. 1 for a DML and an EML illustrate the difference in performance between the two approaches, and the possibility of obtaining better transmission performance with an EML.

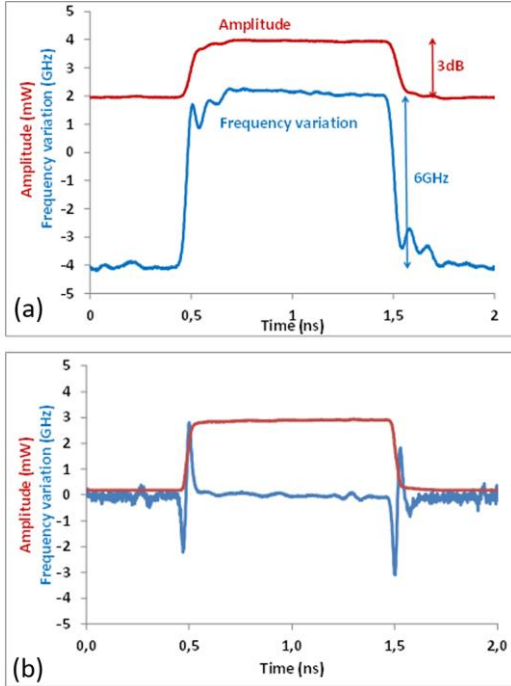


Fig. 1. Illustration of amplitude and frequency variations during a '1' bit for (a) a DML, (b) an EML.

Furthermore, since the EAM is reverse-biased, the modulation mechanism is no longer limited by the carrier injection speed, but by the carrier extraction efficiency under an electric field. This much faster phenomenon allows very high electro-optical bandwidths around 30-40 GHz, which can even approach 60 GHz.

On the other hand, EML requires more complex manufacturing and control, and can be power limited. In addition, the absorption characteristic of the EAM as a function of the applied voltage is highly temperature-

dependent, which makes EMLs difficult to operate uncooled. Many laboratories have been working for years on the optimization of the EML, following different directions depending on the application: increase emitted power, increase modulation speed, reduce power consumption, and/or achieve uncooled operation.

This article presents the progress of our work on EMLs, and the results obtained for different types of applications. Section 2 presents in detail the operation of an EML, the design rules, and the different trade-offs to be taken into account. Section 3 describes our technological approach, its impact on performances, and details the manufacturing process. Section 4 shows how this optimized design has been applied to our C-band EMLs, at 10 or 25 Gb/s, for metropolitan DWDM applications up to 80 km. Section 5 presents a 1577 nm EML for the 10 Gb/s downlink of XGS-PON access networks, optimized for high power. Section 6 shows the latest C-band and O-band results for inter and intra-datacenter applications, aiming at increasing the throughput to 50 and 100 Gb/s PAM4, and to be compatible for uncooled operation. Finally, section 7 presents new developments for the integration of EMLs into a complete subsystem by hybridization on silicon platforms.

II. CONCEPTION

The EML consists of a 400 μ m-long DFB section, monolithically integrated with a 200 μ m-long modulator section, as shown in Fig. 2. The rear facet of the laser is high reflection (HR) coated at 90% to emit all the optical power from the front facet, and the front facet is anti-reflection (AR) coated at 0.01% to reduce optical feedback to the laser section. Both laser and modulator structures are composed of III-V material undoped multi quantum wells (MQWs) on InP substrate, sandwiched between p and n-doped InP claddings, thereby forming a pin heterostructure.

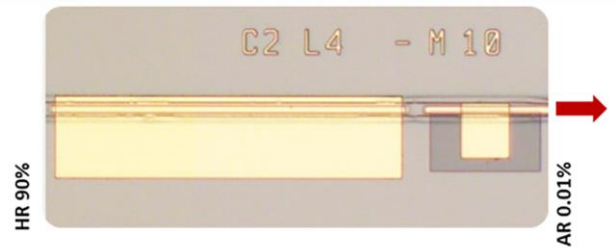


Fig. 2. Optical microscope photography of an EML.

The modulator section is an EAM, based on the Quantum Confined Stark Effect (QCSE) illustrated in Fig. 3a. The MQWs composition is chosen such that without electric field ($V_{EAM} = 0$ V) the MQWs bandgap energy is slightly higher (lower wavelength) than the energy of photons emitted by laser section: the modulator is in transparency mode. When applying a negative voltage on the modulator section, the resulting electric field in undoped MQWs modifies the bandgap structure and reduces the effective bandgap energy: the modulator becomes absorbing. The effect is illustrated in Fig. 3b, where the absorption spectrum of EAM shifts to lower energies when applying a reverse voltage. Fig. 3c shows the

resulting absorption of modulator section versus applied voltage (extinction curve) for various laser emission wavelengths, showing a steep absorption of more than 15 dB at -1V to -2V. Higher laser emission wavelength (λ_4), that is lower energy, requires more voltage to reach maximum extinction. Quantification effect in the wells creates a bounding of electron-hole pairs called exciton: this generates the step-like shape of the absorption, with even a local peak spike at absorption front (Fig. 3b). With applied electrical field, holes and electrons wavefunctions overlap decreases, leading to a damping of exciton peak. The exciton is visible as well with the local sharp minimum in the ER(V) curve (Fig. 3c), and helps to obtain steep extinction curve.

An ideal modulator should be fully transparent at 0 V (no insertion losses), have a steep extinction curve (low peak-to-peak modulation voltage V_{pp}), and sufficient extinction (typically around 15 dB, but variable depending on the application). Several parameters allow the structure to be optimized, as presented below.

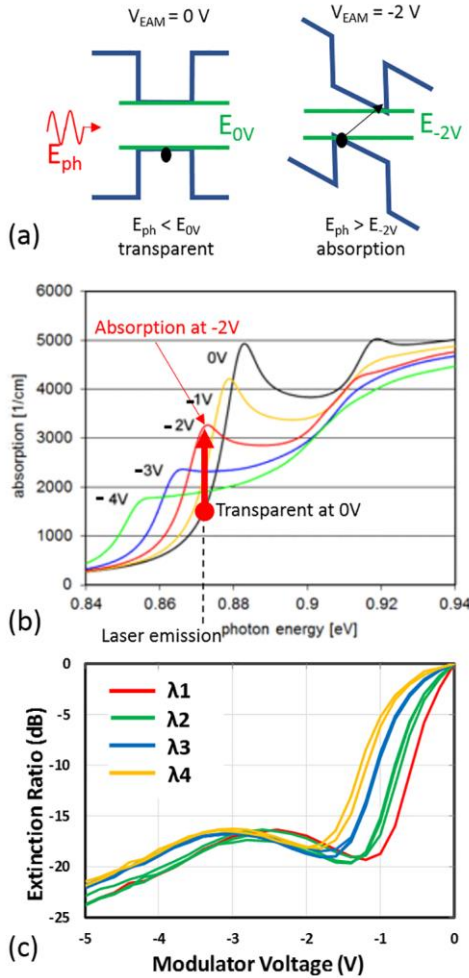


Fig. 3. (a) Principle of QCSE, (b) absorption vs wavelength characteristics for different applied negative voltages, (c) resulting extinction curve of an EAM section for different laser emission wavelengths.

The detuning $\Delta\lambda$ between laser emission wavelength and modulator absorption peak wavelength is a key parameter, as shown in Fig. 3c. A low detuning (λ_1) allows to obtain a very steep extinction but generates insertion losses. This case is

adapted to very low power consumption applications with V_{pp} around 1.2 V (datacenters for example). On the other hand, high detuning (λ_4) reduces losses but increases V_{pp} to almost 2V. Thus, it is preferred for high-power applications (e.g. access networks). Typically, the detuning $\Delta\lambda$ varies between 40 nm and 60 nm.

The thickness of each quantum well also has an important impact. Indeed, the energy shift of absorption front is proportional to $E^2 * (m_e + m_{hh}) * th_{QW}^4$, where E is the applied electric field, m_e and m_{hh} are the effective masses of electrons and holes, and th_{QW} is the quantum wells thickness. In one sense, it is preferable to increase the thickness of quantum wells. But this also reduces the exciton strength, especially under the application of an electric field where the overlap of the wave functions of holes and electrons decreases faster for thick QWs: the extinction curve becomes smoother. The optimum thickness of the quantum well therefore corresponds to the maximum thickness that still guarantees sufficient confinement of the exciton, typically around 9 nm.

Finally, composition of the MQWs is key, and its optimization has been the subject of numerous studies [2], [3], [4]. In order to increase the exciton effect, it is necessary to have highly confined quantum wells with a high barrier height. But this can lead to absorption saturation problems. Under high injected power, photogenerated carriers in the MQW stack of the modulator tend to pile-up, due to their limited sweep-out time, especially for the holes with a higher effective mass and lower mobility. Firstly, this effect prevents the absorption of other photons because energy levels are occupied. Secondly it screens the applied electric field, which is therefore no longer efficiently applied to the MQWs. The ideal structure would therefore have a high conduction band offset (ΔE_c) for strong electrons confinement, and a low valence band offset (ΔE_v) for fast holes sweep-out time. In the InGaAsP-based system, the ratio $\Delta E_c/\Delta E_v$ is around 40 % : 60 %. The optimization then consists in choosing a barrier height just sufficient to maintain a strong exciton under electrical field. We typically use InGaAsP with 1.17 μm photoluminescence (PL) for modulators operating at 1.55 μm , and the barrier with lower PL for modulators operating at 1.3 μm . In addition, tensile strain can be applied to quantum wells such that the first level of valence band is filled by light holes instead of heavy holes, as light holes have the advantage of faster sweep-out time, and stronger exciton link [5].

To further optimize the ratio $\Delta E_c/\Delta E_v$ and to favour uncooled application, many laboratories grow Aluminium-based quantum wells, where the ratio $\Delta E_c/\Delta E_v$ is higher at 70 % : 30 % [5], [6], [7]. However, as Aluminium-based materials which are prone to well-known oxidation issues, they present some constraints in terms of processing compared to Phosphorus-based materials.

Once the structure of the MQW modulators has been chosen, the geometry is adapted according to target specifications, in particular modulation rate and extinction ratio (ER). Under modulation between a voltage V_{on} for bits 1 and V_{off} for bits 0, the ER is defined as the ratio between the ON and OFF powers and is expressed by:

$$ER(dB) = 10 \log(P_{on}/P_{off}) = 10 \log(\exp(-\Gamma \Delta \alpha L)) \quad (1)$$

where Γ is the mode optical confinement in the MQWs, $\Delta \alpha$ is the variation of absorption coefficient in the MQWs per unit length between V_{on} and V_{off} , and L is the length of modulator. Therefore, ER is proportional in dB to the product $\Gamma \Delta \alpha L$.

The choice of modulator length is mainly imposed by the desired modulation rate which defines the minimum electro-optical bandwidth at 3 dB (f_{3dB}) to obtain a clean eye diagram. For example, for 10 Gb/s (resp 25 Gb/s) NRZ modulation the MEA must have a f_{3dB} around 8 GHz (resp 17 GHz). For PAM4 modulation at 28 GBaud (resp 56 GBaud) a f_{3dB} of 20 GHz (resp 35 GHz) will be targeted. Fig. 4 shows a picture of EML soldered on submount, with the electrical connections. Electrical ground is obtained via the solder of the EML underside. The laser electrode is connected to a simple static pad. The modulator electrode is connected to a high frequency (HF) line sandwiched between two ground areas. A 50 Ω resistor is connected in parallel to provide impedance matching with the signal generator. Using a simple equivalent circuit, f_{3dB} can be expressed as:

$$f_{3dB} = \frac{1}{2\pi \left(R_s + \left(\frac{1}{R_g} + \frac{1}{R_L} \right)^{-1} \right) C} \quad (2)$$

with $C = C_j + C_{par} + C_{pad}$

where R_g is the impedance of the voltage generator connected to the EAM, which normally has a value of 50 Ω . The load resistance R_L is the 50 Ω parallel matching resistance added on the submount. The EAM part includes a series resistance R_s (typically several ohms), and a capacitance C which is the sum of the reverse biased p-i-n junction capacitance C_j , parasitic capacitance C_{par} and pad capacitance C_{pad} . In order to increase the 3 dB bandwidth, one needs to reduce the capacitance C . The pad capacitance can be reduced by using small pad (minimum 60 $\mu m \times 60 \mu m$ for wire bonding compatibility) and a thick dielectric layer under metallization, leading to typically 0.1 pF for C_{pad} . The junction capacitance is expressed by $C_j = \epsilon_0 \epsilon_r wL/d$, where ϵ_0 is vacuum permittivity, ϵ_r is undoped MQW structure relative permittivity around 12.5, L is modulator length, and d is undoped layers thickness. Increasing d is detrimental because for a given voltage V , the electric field applied on MQWs is $E=V/d$. Thus, increasing d would directly increase the required V_{pp} . Therefore, modulator length is the main parameter to be adapted according to the required bandwidth. Typically, modulator length is in the range of 200 μm for 10 Gb/s, 150 μm for 25 Gb/s or 25 GBaud, and 100 μm for 56 GBaud.

Then, the confinement Γ in MQWs is adjusted to reach the required ER, by adapting the number of MQW: typically 10 % confinement for 10 Gb/s, and beyond 15 % for more than 25 Gb/s depending on the ER specifications. The price for higher confinement is an increase of undoped MQWs layer thickness d , leading to a higher V_{pp} . For most applications, V_{pp} may be up to 2 V, but for intra-datacenters as described in section 6, it is preferred to keep very low V_{pp} at 0.8 V to reduce electrical consumption, with a moderate extinction ratio of 3.5 dB.

Therefore, in practical designs, the thickness of undoped region and the length of modulator should be compromised to simultaneously optimize three parameters: ER, f_{3dB} , and V_{pp} .

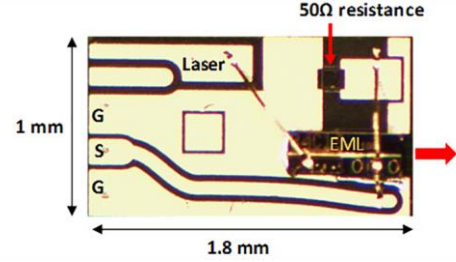


Fig. 4. Photography of an EML mounted on submount, with electrical connections.

As explained in the introduction, the main advantage of EML over DML is the absence of modulation of the laser section, thus the absence of relaxation oscillations of the laser section. However, the EML is extremely sensitive to modulated optical feedback after the modulator section, as it would excite the laser at its resonant frequency and severely degrade the eye diagrams. A feedback smaller than 0.01% (-40 dB) becomes necessary to prevent laser parasitic oscillation. Feedback from the optical system (fiber connectors, couplers, multiplexers, ...) is suppressed by integrating an isolator in the subassembly right at the output of the EML. But feedback from the chip output facet must be suppressed as well. A bi-layer TiO_2 / SiO_2 anti-reflection coating is applied on the output facet, which can provide down to 0.01% reflectivity. But for higher tolerance to coating quality and thereby higher industrial yield, the waveguide can be modified as well to avoid the small amount of reflected light to couple back into the waveguide. A first approach is to use a window section [8], that is a section without waveguiding as illustrated Fig. 5a. With a 25 μm -long window, optical feedback is reduced by about 1:6. The other solution is to tilt the output waveguide [9], as illustrated in Fig. 5b, which reduces feedback by about 1:15 for a 7° tilt. Both approaches can be combined, with tilt and window, leading to feedback reduction of 1:100.

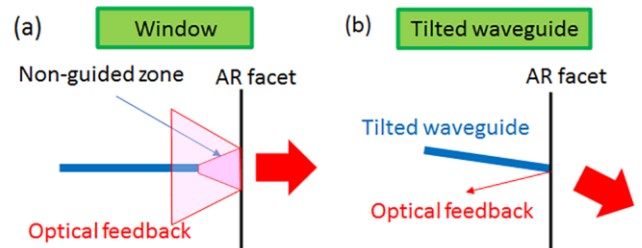


Fig. 5. Schematics. (a) Straight waveguide with window, (b) Tilted waveguide.

To increase the optical power coupled into the fiber at the output of EML, an important parameter is the shape and divergence of the optical mode. It is possible to integrate a Spot Size Converter (SSC) at the output of the EML, allowing the shape of the mode to be progressively modified to reach a larger diameter and a reduced divergence. Our buried technology, presented in the following paragraph, allows to have a circular mode (divergence $22^\circ \times 24^\circ$), and to enlarge it very simply by reducing the waveguide width, with a divergence of $16^\circ \times 18^\circ$ obtained by a narrowing of the ribbon

to 0.7 μm . By using the modulator material, this 75 μm -long SSC does not bring any additional losses.

III. EPITAXY AND FABRICATION PROCESS

Different integration technologies like Quantum Well Intermixing, Selective Area Growth, or Butt Joint Regrowth [10] enable the monolithic integration of different active and passive components while minimizing the impact on the performance of individual components. Almae Technologies uses the widely known butt-joint (BJ) technology because it allows independent optimization of quantum wells in both sections: material composition, doping, number of MQWs and thickness.

Almae technologies employs the InGaAsP material system grown by GSMBE for the MQWs, using a Riber V100 multi 3-inch MBE reactor. Solid sources are used for III elements (In, Ga) whereas V elements As_2 and P_2 molecules stem from the decomposition of AsH_3 and PH_3 gas using a gas cracker. Using gas sources instead of solid sources for elements V enables to do abrupt interface and reproducible layers with different As/P ratio by simply adjusting the PH_3 and AsH_3 flow during a short time of growth stop (~ 10 sec), which is of main importance for the controlled growth of MQWs. Thus, a simple and reproducible method for the growth of InGaAsP MQW by GSMBE is to work with constant element III (fixed In/Ga ratio) and adjust the V element (variable As/P ratio) between the well and the barrier. Moreover, as the wells are compressively strained due to their lattice-mismatch ($\sim 1\%$), strain compensation with tensile strained barriers is useful to prevent the formation of crystalline defects [11].

Once the EAM heterostructure is grown on an InP substrate, a SiO_2 layer is deposited by Plasma-Enhanced Chemical Vapor Deposition (PECVD) and patterned by Reactive Ion Etching (RIE). This patterned SiO_2 is used as a hard mask to define trenches into the EAM vertical structure by chlorine based Inductively Coupled Plasma (ICP). Cleaning and restoration of the surfaces are achieved by a succession of wet etch steps before GSMBE regrowth of the laser vertical structure in the previously ICP etched trenches.

GSMBE presents some advantage over MOVPE for the BJ technology. The anisotropy of molecular beams and the insensitivity of MBE to Selective Area Growth (SAG) effects in the vicinity of the SiO_2 mask make it easier to control the butt-joint regrowth step compared to MOVPE, for which the strategy for EML epitaxial growth is rather to take advantages of SAG effects [12]. As illustrated in Fig. 6, under optimized growth conditions, GSMBE deposits polycrystals on top of the SiO_2 mask, which are removed through lift-off, leading to an abrupt interface between the laser and the modulator sections.

Precise vertical alignment of the EAM and Laser MQWs as well as similar effective index for both regions are mandatory to limit the scattering and reflection losses at butt-joint interfaces.

In order to obtain a DFB laser, Electron beam (E-beam) lithography is used to pattern a Bragg grating in a dedicated layer on top of the laser structure. The grating pitch is adapted according to the desired wavelength. After an ICP etching of

the grating layer, grating teeth are filled by 300 nm of p-doped InP grown by GSMBE for planarization (Fig. 7a).

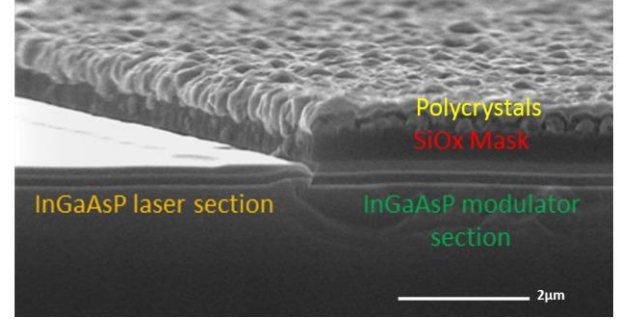


Fig. 6. SEM cross-section observation of a BJ regrowth done at Almae technology, showing the laser and the modulator sections.

Afterwards, waveguides are defined by optical contact lithography and then etched by ICP. Semi Insulated Buried Heterostructure (SIBH) regrowth performed by MOVPE is used to laterally bury the waveguide with iron doped semi-insulating InP (Fig. 7b), which prevents lateral leakage current and allows an efficient thermal dissipation, high speed modulation compatibility, circular optical mode and chip mechanical robustness.

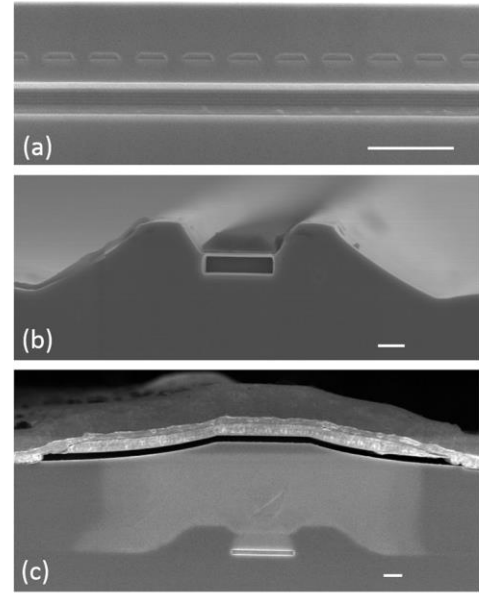


Fig. 7. Cross-sectional SEM images of (a) buried grating layer, (b) SIBH regrowth with SiO_2 mask, and (c) final device. Scale bar: 500 nm.

Afterwards, GSMBE is used to grow the final cladding layer composed of P-doped InP and a ternary contact layer. The possibility of using Beryllium p-type dopant with GSMBE instead of Zinc dopant in MOVPE is of main interest for the P regrowth steps in the EML process. Indeed, the nature of the dopant species and the lower temperature of the MBE growth of InP ($\sim 450^\circ\text{C}$) than MOVPE growth ($\sim 650^\circ\text{C}$) enable to limit dopants diffusion into the MQWs by substitutional-interstitial diffusion mechanisms [13]. The lower diffusion of Be dopant during the P cladding regrowth by GSMBE will allow to ensure a fully non-doped MQWs stack leading to a uniform application of the dielectric field (Poisson's law) along all the MQWs. Therefore, as illustrated in Fig. 8, we obtain a stepper EAM extinction response

compared to Zn based P cladding regrowth by MOVPE.

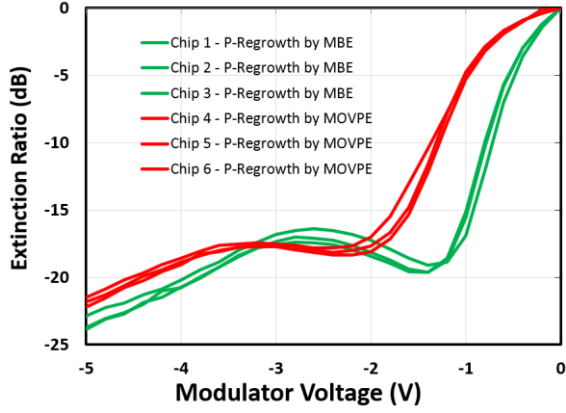


Fig. 8. EAM extinction response of EMLs with Zn P-doped cladding by MOVPE (in red) and with Be P-doped cladding by MBE (in green).

Metal contacts on the P-side are then defined by a lift-off process of Platinum / Gold deposited by electron beam evaporation. A 390 °C Rapid Thermal Annealing (RTA) permits diffusion of the Pt into the ternary contact layer to ensure an ohmic electrical contact and prevent gold diffusion into the semiconductor.

To reduce modulator capacitance and to electrically isolate laser and modulator sections, H⁺ ions are locally implanted, turning top p-InP into insulating material. An ICP etching step of the ternary contact layer completes this implantation by physically isolating the EAM from the DFB.

To prevent parasitic capacitance of the EAM electrodes, a 2 μm-thick SiO₂ layer is deposited by PECVD and patterned by RIE to define a SiO₂ pad below the EAM interconnection contact. That low capacitance pad coupled with SIBH regrowth technology allows to achieve high modulation bandwidth for the modulator. The next process step consists in depositing interconnection metal pads for laser and modulator to ease wire bonding of the EML electrodes during packaging steps (Fig. 7c).

The InP substrate is then thinned down to ensure precise cleaving of the optoelectronic devices while preventing damage on their optical facets. A Titanium / Platinum / Gold stack is then evaporated on the wafer N-side to define the N-type metallic contact.

IV. EML FOR 1550 NM AND 1577 NM APPLICATIONS

A. C-band 10 and 25 Gb/s EML

A first field of application of EML is C-band transmission for metropolitan networks. Modulation at a moderate rate of 10 Gb/s is utilized in order to reach distances of 40 to 80 km despite the chromatic dispersion of the fibers. A high total data rate can be achieved by DWDM, with 40 channels spaced at 100 GHz (0.8 nm wavelength), or 80 channels spaced at 50 GHz (0.4 nm), covering the entire C-band (about 1525-1565 nm). These applications typically require operation at 45 °C to reduce Peltier consumption, on-chip facet average modulated power (P_{ave}) of 4 dBm, with a 9 dB dynamic extinction ratio (DER) and a peak-to-peak modulation voltage (V_{pp}) of less than 2 V.

These EMLs benefit from our steep extinction curves. The detuning $\Delta\lambda$ between the laser emission wavelength and the absorption front of the modulator is minimized to about 45 nm in order to reduce V_{pp} , while maintaining low insertion losses at $V_{EAM} = 0$ V.

The characteristic performance at 45 °C is shown in Fig. 9a-e. Fig. 9a shows the facet power and voltage as a function of laser current when the modulator is at 0 V. A laser power larger to 10 mW is reached at 70 mA, with a low 3.6 Ω serial resistance. The optical spectrum is shown in Fig. 9b with $I_{laser} = 70$ mA, yielding single mode operation and Side Mode Suppression Ratio (SMSR) beyond 50 dB. Fig. 9c shows the modulator ER as a function of the modulator voltage when $I_{laser} = 70$ mA. A 17 dB maximum ER is obtained for $V_{EAM} = -1.3$ V. The dynamic characterization of this device is shown in Fig. 9d-e. In Fig. 9d the electro-optical bandwidth of the device is represented when $I_{laser} = 70$ mA and $V_{EAM} = -0.5$ V. Under these conditions a f_{3dB} of 18 GHz is reached, largely fulfilling the requirements for 10 Gb/s applications. Fig. 9e shows the eye diagram for a bit rate of 10 Gb/s with $I_{laser} = 70$ mA and $V_{EAM} = 1.5$ V. All the characteristics required for metropolitan application are obtained, with $P_{ave} = 7$ dBm, and a dynamic extinction ratio (DER) of 12.3 dB. The e-beam technique used for DFB laser gratings writing allows to cover 5 nm wavelength range on a single wafer, which is a key economical asset when needing to cover the whole C-band. With a bandwidth of 18 GHz, these components can even be used for shorter-distance applications of the order of 10 km, e.g. in access networks at data rates of 25 Gb/s [14].

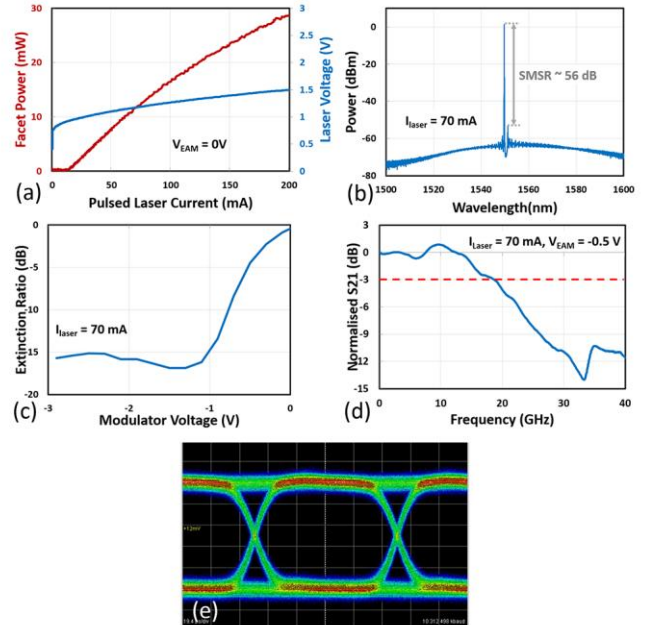


Fig. 9. Measurements of a 10 Gb/s DWDM C-band EML at 45°C. (a) Facet power and voltage versus laser current (pulsed). (b) Optical spectrum at 70 mA. (c) Modulator steep extinction curve at $I_{laser} = 70$ mA. (d) Electro-Optical bandwidth of modulator at $I_{laser} = 70$ mA and $V_{EAM} = -0.5$ V. (e) Eye diagram at 10Gb/s for $I_{laser} = 70$ mA and $V_{pp} = 1.5$ V.

These components, currently in production at Almae Technologies, systematically endure a burn-in with stressful conditions ($I_{laser} = 175$ mA / $V_{EAM} = -1$ V / 100 °C / 18 h), in order to eliminate youth defects and fragile devices. Then the

design was qualified by subjecting a large batch of chips to accelerated ageing ($I_{\text{laser}} = 100 \text{ mA}$ / $V_{\text{EAM}} = -1 \text{ V}$ / 85°C / 5000 h). Considering a total acceleration factor of 50, this corresponds to an operating life of 70 mA / 45°C of more than 25 years.

B. 1577nm high-power EMLs for access networks

Access networks are the final link between the Optical Line Terminal (OLT) of the network, and the Optical Network Unit (ONU) at the user's side, which can be a private house, a building, a company, a public building, ... These access networks have developed extremely fast, in particular with smartphones, 4G, and now 5G. Covering typical distances of 20 to 40 km, they are based on Passive Optical Networks (PON), i.e. networks without optical amplification, but only with splitters / combiners or multiplexers / demultiplexers. The main constraint on the optical components is therefore to reach the power budget of the link, typically around 30 dB. For this, the system is based on high-power transmitters, and on high sensitivity avalanche photodiodes (APDs) receivers. The second constraint is the cost, especially for components located at the ONU subscriber's premises.

The Full Service Access Network (FSAN) group proposes a GPON (Gigabit PON) evolution roadmap, and ITU standards have been defined for two approaches: NG-PON2 which is a wavelength division multiplexed system, or XGS-PON with 10 Gb/s downstream and upstream data rates [15], [16]. Access networks must enable the coexistence of different standards on the same links, despite their specific data rates and slightly different wavelength ranges. A typical network link is shown in Fig. 10. For upstream, the wavelengths are O-band, around 1260-1280 nm for XGS-PON and 1310 nm for GPON. Low chromatic dispersion allows the employment of low-cost DMLs, at 2.5 Gb/s or 10 Gb/s, in the ONU. For downstream, the wavelengths are 1577 nm for XGS-PON and 1490 nm for GPON, which requires the use of EMLs at the OLT to transmit despite the chromatic dispersion. The multitude of users is served via splitters and combiners, leading to a high-power budget in the range of 29 to 35 dB depending on network characteristics (link distances, number of users).

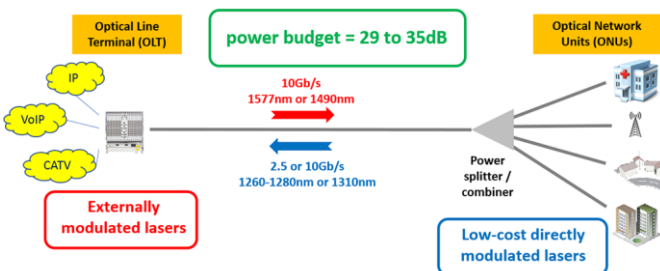


Fig. 10. Schematic of next generation PON network.

XGS-PON networks therefore require a high-power EML transmitting at 1577 nm, used in the OLT. The EML is packaged in a Bi-directional Optical Sub-Assembly (BOSA) module shown in Fig. 11, which contains both the EML transmitter and APD receiver. Two transmitter power classes, called N1 and N2, are standardized for different optical budget

ranges. Class N1 requires BOSA transmitter power from 2 to 6 dBm, and class N2 from 4 to 8 dBm. Considering assembly losses about 4.5 dB in BOSA, this corresponds to EML facet modulated power P_{ave} higher than 6.5 dBm for N1 and 8.5 dBm for N2.

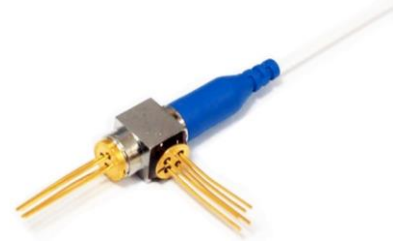


Fig. 11. Photography of a BOSA module, containing both 1577 nm transmitter and O-band APD receiver.

For this purpose, we have developed a specific high-power EML design with the same 200 μm -long EAM section, but with a 10 nm wider laser – modulator detuning $\Delta\lambda$, in order to minimize insertion losses by the modulator. The results at 45°C are presented in Fig. 12. Fig. 12a shows the ER as a function of modulator voltage at $I_{\text{laser}} = 70 \text{ mA}$. As detuning λ_1 has been increased, the maximum 17 dB ER is obtained for a slightly larger voltage of -1.6 V. Fig. 12b shows the eye diagram at 10 Gb/s, with $V_{\text{pp}} = 2.5 \text{ V}$, at $I_{\text{laser}} = 100 \text{ mA}$, demonstrating a DER of 12.4 dB and P_{ave} of 8 dBm, compatible with N1 and N2 applications.

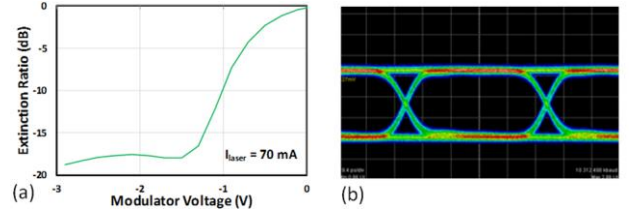


Fig. 12. (a) Static ER for an EMLs with a 200 μm -long EAM at 45°C . (b) 10 Gb/s eye diagram with $I_{\text{laser}} = 100 \text{ mA}$ and $V_{\text{EAM}} = 2.5 \text{ V}$ at 45°C .

In order to further increase the number of users per OLT and/or to cover larger geographical areas, a new standard with higher optical budget appears. This is the class E1, with a power emitted by the BOSA of 6 to 9 dBm, corresponding to P_{ave} greater than 10.5 dBm. To achieve this, the first step is to increase the power emitted by the laser by using a higher current, but this leads to a modulator saturation phenomenon as explained in section II. The impact on performances is a longer fall time on the eye diagrams, visible in Fig. 13c-d.

To mitigate this saturation, a first approach illustrated in Fig. 13 consists in further increasing the laser-modulator detuning $\Delta\lambda$. Modulator insertion losses during "1" bit is reduced. And as the ER(V) curve is shifted to higher voltages, a stronger electric field is applied on the modulator MQW, thus reducing the holes sweep-out time. By slightly lengthening modulator section, the extinction ratio can be maintained to the required value. The impact of $\Delta\lambda$ on EML characteristics is illustrated Fig. 13 for a 250 μm -long EAM, for three $\Delta\lambda$ values separated by 8 nm. Fig. 13a presents the optical spectra for three chips with different detunings of $\Delta\lambda = 46 \text{ nm}$ (blue line), $\Delta\lambda = 54 \text{ nm}$ (green line) and $\Delta\lambda = 62 \text{ nm}$ (red line), respectively. All measurements are realized with the same conditions ($I_{\text{laser}} = 70 \text{ mA}$ at 45°C). Fig. 13b shows the

laser facet power as a function of the laser current for three chips with different detunings at $V_{EAM} = 0V$. We observe highest power for the highest detuning, red line, due to reduced insertion losses. The eye diagrams at a modulation bit rate of 10 Gb/s, measured with $I_{laser}=150$ mA at 45 °C, for low ($\Delta\lambda = 46$ nm), medium ($\Delta\lambda = 54$ nm) and high ($\Delta\lambda = 62$ nm) detunings are represented in Fig. 13c, d and e, respectively. The eye diagrams of the EMLs with low and medium detuning are distorted by the modulation saturation phenomenon (Fig. 13c-d), in particular with a slower fall time. As illustrated in Fig. 13e, the EML with highest detuning ($\Delta\lambda = 62$ nm) presents a clean eye diagram with a P_{ave} of 10.6 dBm and a DER of 11.6 dB, without saturation effect, compatible for class E1. This eye diagram is achieved using a modulator voltage of 2.9 V.

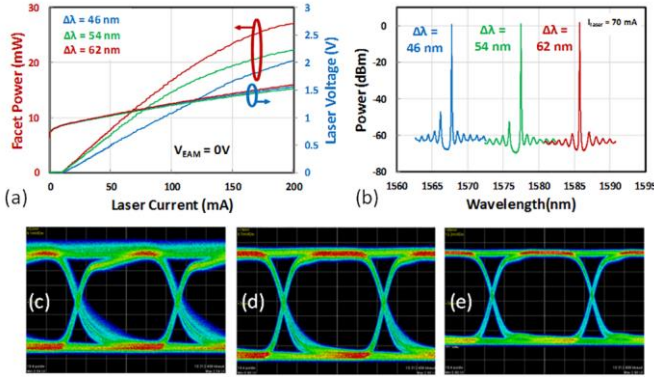


Fig. 13. Study at 45 °C of performances of EMLs with 250 μ m-long EAM, and different laser-modulator detunings $\Delta\lambda$ of 46 nm (blue), 54 nm (green) and 62 nm (red). (a) Facet power and laser voltage as a function of the laser current at $V_{EAM} = 0$ V (b) Optical spectrum for three chips with different detunings with $I_{laser} = 70$ mA. 10 Gb/s eye diagrams at $I_{laser} = 150$ mA (c) for $\Delta\lambda = 46$ nm obtaining DER = 13.5 dB and $P_{ave} = 7.3$ dBm with $V_{pp} = 2.5$ V. (d) $\Delta\lambda = 54$ nm reaching DER = 12.4dB, $P_{ave} = 9.9$ dBm with $V_{pp} = 2.7$ V and (e) with $\Delta\lambda = 62$ nm obtaining DER = 11.6 dB and $P_{ave} = 10.6$ dBm with $V_{pp} = 2.9$ V.

A second approach is to operate the EML at moderate power, but to integrate a Semiconductor Optical Amplifier (SOA) section as a booster after the modulator. This solution eliminates saturation problems in the modulator and can even increase the transmission distance by a chirp compensation effect. Shindo *et al.* have developed an EML-SOA and demonstrated for 1577 nm applications with 4.9 dB of gain provided by the SOA, allowing to reach a P_{ave} of 9 dBm [17]. The EML-SOA approach remains delicate because in order to avoid too many perturbations brought by the SOA, it is preferable to operate at least 3 dB below its saturation regime, which limits the maximum emitted power. In addition, the SOA amplifies the optical feedback, which is very detrimental to the EML. Furthermore, even without optical feedback, the spontaneous emission generated by SOA is modulated by the modulator section and thus may disturb the laser.

A third approach is to modulate both the laser section and the modulator section, with a Laser-Modulated EML (LM-EML). During "0", the laser emitting power reduced when the modulator absorbs the light. This limits saturation phenomena since the input power to the modulator is decreased and reduces the power consumption by avoiding unnecessary generation of photons absorbed by the modulator. The

limitation of this approach is the requirement for an additional driver for the laser, and the possible degradation of transmission performance due to the direct modulation of the laser. Depending on the applications, in particular on the wavelength range (low chromatic dispersion O-band or C-band) and the bit rate, the modulation ratio between laser and modulator sections can be optimized. For applications at 1577 nm, a gain of 2 dB in optical power has been demonstrated [18].

V. EML FOR HIGH-SPEED AND UNCOOLED APPLICATIONS

The explosive growth of traffic is driving a huge demand for high-capacity data center infrastructure for higher bandwidth. Typical optical interconnects can cover up to 500 meters. Copper direct attach cables are used for connections below 5 m. While between top of rack and leaf level, up to 100-500 m, the multimode active optical cables and transceivers, like VCSELs are widely used. With the increment of distance and requirement for higher data rate, deployment of single mode fiber becomes necessary, either by Parallel Single Mode 4-channel (PSM4), coarse wavelength division multiplexing (CWDM), or local area network wavelength division multiplexing (LAN-WDM) technologies. Intra-datacenter connections require low cost (including the transceivers together with the fibers), low power consumption and high bandwidth density. Transmitters must operate uncooled, without any Peltier control, in order to reduce consumption. And the trend is to increase data rates per lane towards 100 Gb/s with 56 GBaud PAM4 modulation formats, for which DMLs reach their performance limits, opening the way to uncooled EMLs (20 to 70 °C).

However, uncooled operation is particularly challenging for EML because the laser-modulator detuning $\Delta\lambda$ decreases rapidly with temperature. At low temperature, the high detuning results in a smooth extinction curve and a high V_{pp} . At high temperature, the detuning is low, leading to high insertion loss of the EAM. Thus, it is desired to have a very steep extinction curve to maintain low V_{pp} and high power over a broad temperature range.

Aluminium-based MQWs are widespread used for very high temperature operation, both for laser and modulator sections, due to their stronger electron confinement in the conduction band [5], [6]. However, for temperature ranges up to 70°C, Phosphorus-based MQWs with high bandgap energy barriers can remain performant [7].

For these high-speed intra-datacenter connections, CWDM O-band EMLs are generally deployed. But for short distances, CWDM C-band EMLs could be of interest as well, to increase the number of available channels. Almae demonstrated functional uncooled EMLs working in both C-band [19] and recently extended it to O-band.

A. C-band uncooled EML

As illustrated Fig. 14a, laser Bragg wavelength shifts with temperature by 0.1 nm/°C, much slower than laser maximum gain which shifts by 0.6 nm/°C due to semiconductor crystal dilatation. Therefore, the laser photoluminescence is chosen to

have a positive detuning of Bragg wavelength at 20 °C, which becomes null around 50 °C, and slightly negative at 70 °C (SMSR remains above 45 dB for all temperatures).

Fig. 14b plots the facet power versus pulsed laser current, with the EAM connected to ground. Thanks to the initial positive laser Bragg detuning, and to the high detuning $\Delta\lambda$, facet power remains at 7.5 mW for laser operating at 150 mA / 70 °C. (The C-band EML mentioned here is based on modulator length of 150 μm).

Fig. 14c corresponds to the EAM extinction curve for 70 mA laser current. Similar to laser gain, the EAM absorption front wavelength shifts by 0.6 nm/°C while DFB wavelength shifts by only 0.1 nm/°C, leading to a $\Delta\lambda$ reduction of 0.5 nm/°C. For operation between 20 to 70 °C, it corresponds to a $\Delta\lambda$ variation as large as 25 nm. The EAM stack optimization and the choice of a high $\Delta\lambda$ provide an optimum trade-off with still steep extinction curve at 20 °C, and moderate insertion loss at 70 °C.

We studied the uncooled behavior of our EMLs with 28 Gb/s NRZ modulation, focusing on reducing V_{pp} and increasing output power.

Fig. 14d shows the electro-optical bandwidth for temperature ranging between 20 °C and 70 °C. Laser current is fixed at 100mA and EAM bias at -0.5V. The dip observed at 13 GHz is attributed to the submount design. The intrinsic bandwidth varies between 18 GHz and 20 GHz.

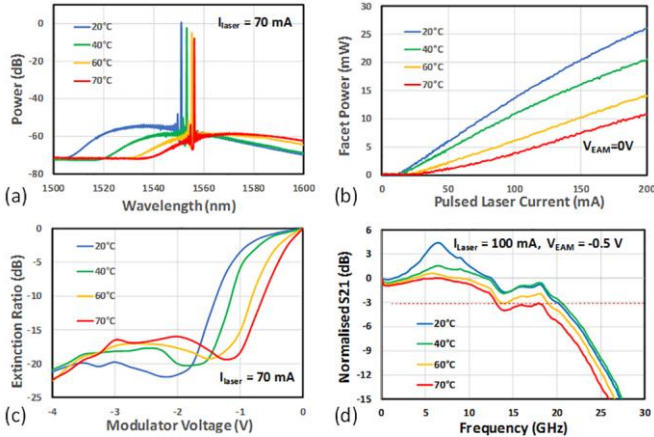


Fig. 14. Characteristics from 20 °C to 70 °C of a C-band EML chip on submount. (a) Optical spectra, (b) L(I) curve with pulsed current source, (c) static ER at $I_{\text{laser}} = 70$ mA. (d) Electro-Optical bandwidth at $I_{\text{laser}} = 100$ mA and $V_{\text{EAM}} = -0.5$ V.

As illustrated Fig. 15, we collected 28Gb/s NRZ eye diagrams at 20 °C, 40 °C, 60 °C and 70 °C. For each temperature, we tested operation for different values of V_{pp} (0.9 V, 1.2 V, and 1.6 V), and adjusted on-state EAM voltage V_{on} to obtain highest output power while keeping optimal eye opening with 50% crossing point. Laser is biased at 70 mA, 100 mA or 150 mA to maintain high output power, especially at high temperature. The output power after modulation is collected in the fiber and corrected by the measured fiber coupling loss of 3.9 dB to assess modulated facet power P_{ave} .

It should be noted that thermal contact is not optimum for this test configuration on submount, compared to operation in module. Laser thermal resistance of 65 °C/W is measured: results at 70 °C / 150 mA are pessimistic as they correspond to

laser chip temperature of about 83 °C.

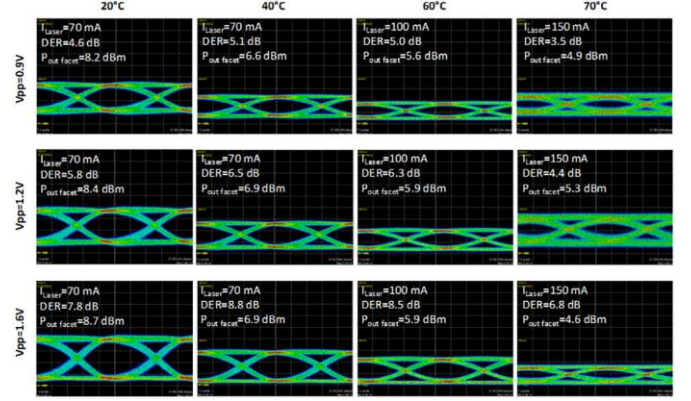


Fig. 15. 28 Gb/s eye diagrams at 20 °C, 40 °C, 60 °C and 70 °C with V_{pp} equal to 0.9 V, 1.2 V and 1.6 V.

Clear eye openings are obtained for all temperatures. Eye diagrams at 70 °C appear slightly noisier due to lower input power into the oscilloscope. The temperature dependence of DER and P_{ave} are summarized in Fig. 16. From 20 °C to 70 °C, DER of more than 3.5 dB is obtained even with V_{pp} of 0.9 V, and over 6.7 dB with V_{pp} of 1.6 V. P_{ave} ranges between about 8.5 dBm at 20 °C / 70 mA and 5 dBm and at 70 °C / 150 mA.

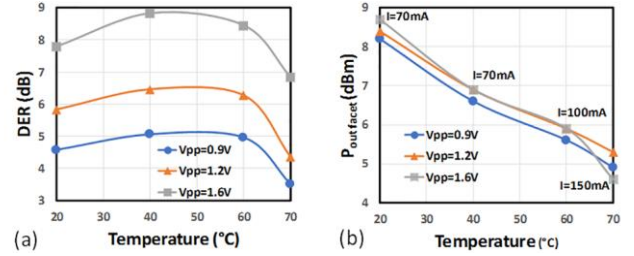


Fig. 16. Summary of temperature dependence of (a) dynamic extinction ratio, (b) facet modulated output power.

B. O-band uncooled EML

Recently, we have deployed uncooled EMLs for O-band as well. We tried to further improve the output power at high temperature, and the bit rate for 56 GBaud [20]. To optimize the thermal performances of our Phosphorus-based laser MQWs, we used several solid source of Indium and/or Gallium during GSMBE growth to add limited but appreciable degrees of freedom on the In / Ga ratio between the well and the barrier. This allows us to tailor the MQWs band structure and reach a 55 % : 45 % $\Delta E_C / \Delta E_V$, closer to Al-based systems. We utilized this laser structure together with modulator length of 125 μm to demonstrate the following device performance. Fig. 17a plots the emitted spectra with temperature with almost zero detuning between laser maximum gain and Bragg wavelength around 45 °C. Fig. 17b illustrates facet power curves versus pulsed laser current. Higher output power is observed from 20 °C to 70 °C compared to the performance of above-mentioned C-band uncooled EML, thanks to the lower Inter-Valence Band Absorption (IVBA) effect at 1.3 μm , and to the introduction of new strained Phosphorus-based material system with larger $\Delta E_C / \Delta E_V$. Fig. 17c shows the EAM extinction curve for 70 mA laser current. The extinction curve could be further optimized

by increasing the number of quantum wells. Electro-optical bandwidth at 20 °C is shown in Fig. 17d, with laser current of 100 mA and modulator bias of -1 V, showing a f_{3dB} around 27 GHz.

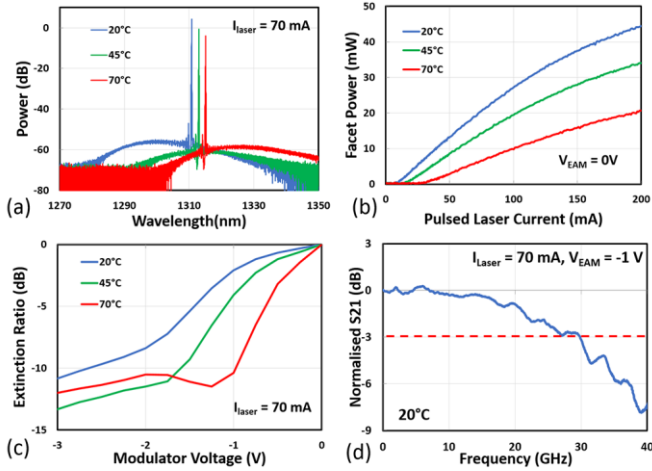


Fig. 17. Static characteristics from 20 °C to 70 °C of a C-band EML chip on submount (a) optical spectra, (b) L(I) curve with pulsed current source, (c) static extinction ratio at $I_{laser} = 70$ mA, (d) S21 at 20°C with laser current fixed at 100 mA and EAM bias of -0.5 V.

28 Gb/s NRZ eye diagrams were collected at 25 °C, 45 °C and 70 °C with different V_{pp} of 1 V, 1.2 V and 1.5 V. Laser is biased at 30 mA, 50 mA or 100 mA to maintain high output power. Clear eye openings are obtained for all temperatures (Fig. 18). As for C-band EML measurements, non-optimum thermal contact is not favorable and leads to an increased real temperature chip. DER augments with temperature: lowest DER of 3.9 dB is observed at 20 °C with V_{pp} of 1 V, while the highest DER of 8.2 dB is obtained at 70 °C with V_{pp} of 1.5 V. The output power can be maintained above 4.2 dBm for all temperatures by adjusting laser current.

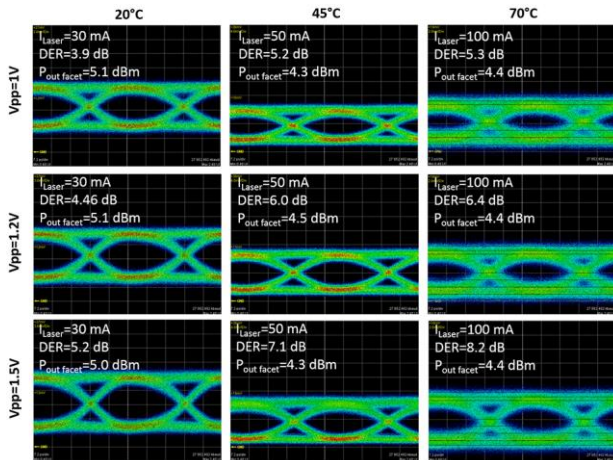


Fig. 18. 28 Gb/s eye diagrams at 20 °C, 45 °C, and 70 °C with V_{pp} equal to 1 V, 1.2 V and 1.5 V.

Fig. 19 shows the relationship between modulator length and DER at the fixed laser current of 50 mA and temperature of 45 °C. DER is increasing linearly with increased modulator length at all V_{pp} . The f_{3dB} has also been measured, showing around 27 GHz for EAM length of 125 μ m, and around 31 GHz for length of 100 μ m. Thus, it is expected to have a functional EML for 56 Gbaud PAM4 with modulator length

around 75 μ m, while the DER can be further optimized by slightly increasing the number of QWs in modulator. Besides, the compatibility with very low V_{pp} offers the possibility to integrate the modulator directly with CMOS circuit for further power consumption reduction.

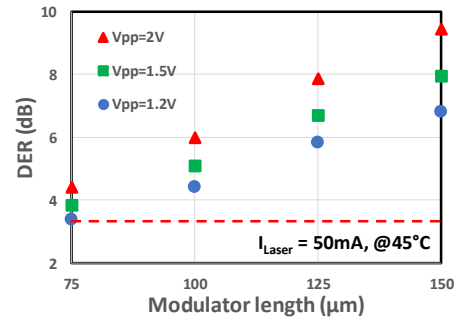


Fig. 19. Relationship between modulator length and dynamic extinction ratio at different V_{pp} .

VI. EMLS IN SUBASSEMBLY AND FURTHER DEVELOPMENTS

The tremendous growth of data traffic drives the technology to higher modulation speed and multi-level modulation (56 Gbaud PAM4), and to transmitters parallelization with 4×50 Gbaud PAM4 for 400 Gb/s or 8×50 Gbaud for 800 Gb/s transmitters. Beyond exploiting the performance of EML chip, the optimization of the module packaging is also highly critical, to ensure efficient thermal dissipation, high-speed HF driving to the EAM, and low-cost / high yield assembly techniques.

In a standard approach, the EMLs are soldered on individual submounts with wire bondings for electrical connections as illustrated Fig. 4. However, the parasitic inductance induced by the bonding wire degrades the electrical characteristics of the EA modulator modules in the high-frequency region which becomes highly detrimental for 56 Gbaud modulation rates [21]. Then each EML is coupled to the output fiber via accurate positioning of lenses and isolators. This operation is so critical and time consuming that more than 90 % of a transmitter price is due to packaging.

Multiple laboratories have worked on more efficient assembly solutions, generally based on arrays of EMLs monolithically integrated on the same substrate, and on the use of flip-chip technology rather than soldering by the chip bottom side to improve HF performances [22], [23], [24].

We are developing as well, in the frame of a European project APPLAUSE, a flip-chip assembly for 4 uncooled 56 Gbaud EMLs, enabling passive optical alignment with Silicon Photonics waveguides. An array of 4 EMLs is flip chipped on a Silicon submount with HF lines, connected by direct soldering to the electrodes. This enables to finely optimize the whole HF line (including the EAM section) for the most efficient transmission of HF electrical signal from the driver to the EAM.

Thanks to the SIBH technology and direct soldering of laser and modulator sections, the thermal dissipation is optimum, enabling to reduce each device self-heating, and thermal crosstalk between adjacent EMLs.

In addition, a specific process has been defined to passively align the EML waveguides with optical fibers accurately positioned into grooves etched on the submount (Fig. 20). To ensure perfect alignment, mechanical recesses in X, Y and Z directions are processed on the EML chip, together with waveguide definition, and corresponding stoppers are defined on the Silicon submount together with fiber V-grooves definition. Owing to the AuSn soldering attraction strength, the EML chip recesses are automatically positioned against the corresponding silicon stoppers, leading to automatic passive alignment. This approach represents a great step forward to reach high yields, low costs, and high performances.

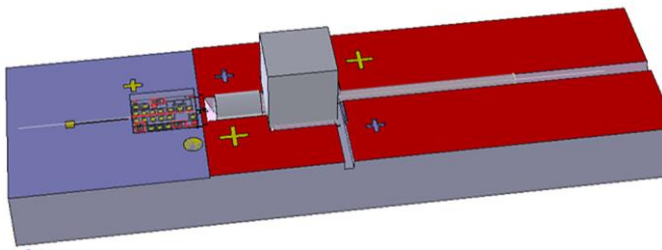


Fig. 20. 3D schematic of a submount with the EML chip, optical interface and V-groove for fiber.

VII. CONCLUSION

We have demonstrated uncooled 28 Gb/s C-band and O-band EML with Phosphorus-based MQWs, butt-joint and SIBH technologies. Through the design of modulator MQW structure, doping profile control, and detuning DFB-EAM between the Bragg wavelength and modulator absorption edge, we obtained a steep modulator extinction curve and high output power. These results are promising for high-speed intra-datacenter transmissions.

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Hélène Debrégeas received Engineering degree from Telecom ParisTech in 1994, Mathematics Agrégation teaching certificate in 1995, and Ph.D on widely tunable lasers in 2007. Since 1997 she has worked at Alcatel Research center (now Nokia Bell Labs, within III-V Lab) on InP transmitters such as electro-absorption modulated lasers, widely tunable laser,

and hybrid integration of InP transmitters and silica passive waveguides. Since 2018 she has joined Almae Technologies to develop next generation products and their hybridization with other technologies or packaging. She contributed to more than 50 peer-reviewed journal and conference papers, 20 patents, and a Springer book chapter on widely tunable lasers.



Guillaume Da Rold has been working with Almae since June 2017 as production manager and cleanroom R&D engineer. He works on the manufacturing and development of EML 10G. He obtained his PhD in process engineering in 2009 from the Pierre and Marie Curie University. During his thesis, he worked on the ageing of materials for space applications.

Between 2010 and 2011, he worked on laser component fabrication at the III-V lab. Then he worked for 5 years in a start-up called Klearia on the fabrication of glass microfluidic chips for real-time monitoring of pollutants in water.



David Carrara received in 2008 his Master degree in Materials and Nanotechnologies from INSA Rennes. From 2009 to 2012, he has pursued a Ph.D. at III-V Lab where he developed new Photonic Integrated Circuits on InP for the generation of advanced modulation formats. In 2012, he joined, as the first employee, the startup Prestodiag in order

to develop and industrialize a new optical technology based on Surface Plasmon Resonance to detect pathogen bacteria in the food market. In 2015, he signed up in III-V Lab to study the conception and fabrication of Silicon Photonic Circuits. Since 2017, he has been working for Almae Technologies where he manages a R&D team working on fabricating high speed

Laser sources. Today, Mr. Carrara holds two patents, one in Optoelectronics and one in Biotechnologies.



Kevin Louarn received his M.Sc. degree in Material Science from the Grenoble INP Institute of Engineering, France in 2014. He then received his Ph.D degree from Laboratory of Analysis and Architecture of Systems of Toulouse, France in 2018. His Ph.D work was focused on the numerical simulation, the epitaxial growth by MBE, the

technological fabrication and the characterisation of tunnel junction and high efficiency multi-junction solar cells based on GaAs substrates. He has been working as a R&D engineer in MBE at Almae Technologies since 2018.



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François Lelarge has been working with Almae technologies as the chief technological officer since 2016. He received the Diploma in Material Science in 1993 and the PhD degree in 1996, both from the University of Pierre et Marie Curie, Paris, France. From 1993 to 1996, he was with the Laboratory of Microstructures and Microelectronic,

CNRS Bagneux, France. His thesis work was devoted to the fabrication and the optical characterization of GaAs/AlAs lateral superlattice grown on vicinal surfaces by MBE. From 1997 to 2000, he was a postdoctoral researcher at the Institute of Micro and Optoelectronics, Lausanne, Switzerland. He worked on InGaAs/GaAs quantum wires fabrication by MOCVD regrowth on patterned substrates. He was in charge of the Epitaxy and New Material Technology team within III-V Lab and coordinator of a project on QD-based directly modulated lasers (ANR-DIQDOT). He has published more than 300 papers and communications in national and international conferences, including invited talks and postdeadline papers.