Long-Wavelength InP VCSEL Exploitation for Innovative Sustainable High-Capacity Transmitter

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***Abstract*—This electronic document is a "live" template and already defines the components of your paper [title, text, heads, etc.] in its style sheet. **CRITICAL: Do Not Use Symbols, Special Characters, Footnotes, or Math in Paper Title or Abstract.* (*Abstract*)**

Keywords—VCSEL, DMT, PIC, SOI

I. Introduction

Exploitation of long-wavelength InP vertical cavity surface emitting lasers (VCSELs) [1,2] is presented to implement a high capacity multi-channel transmitter (TX), designed and developed in the H2020 research project PASSION [3]. VCSELs are directly modulated with multicarrier modulation formats, such as discrete multi-tone (DMT) modulation [4,5], which allows to achieve at least 50 Gb/s rate per VCSEL thanks to bit and power loading, also in presence of limited modulation electrical bandwidth. InP VCSEL employment assures to move the well-known advantages of VCSELs in terms of sustainability (low cost, energy efficiency and reduced footprint) [6,7], already exploited for datacom interconnections, also in different applications, such as enterprise connections, 5G x-haul networks, and metropolitan area networks (MANs), where dense wavelength-division multiplexing (WDM) in the C band is necessary to increase the total aggregated throughput transported in the network. In this paper we describe a TX, integrating 40 VCSELs covering the C band in a single silicon-on-insulator (SOI) module to provide an aggregated capacity up to 2-Tb/s capacity. Heterogeneous integration is exploited, combined with optical 45° mirrors in up-reflecting configuration for VCSEL-Si waveguide coupling. The dimension of the realized photonic integrated circuit (PIC) is about 2cmx2cm, with a power consumption less than 5 pJ/bit, for a total transmitted capacity of 2 Tb/s. The employed land grid array (LGA) interposer designed to provide interconnection and thermal decoupling capabilities to the Si-PIC is described in detail, in order to achieve a compact and thermally efficient module. A modular approach is also pursued, in order to use the same identical 2-Tb/s TX module to build a super-module targeting up to 16 Tb/s capacity. The developed VCSEL-based TX module appears very promising to face the request of huge capacity and traffic scalability in a next-generation sustainable MANs.

II. Directly-modulated long-wavelength VCSELs

Short-wavelength multi-mode GaAs VCSELs are now widely used for high-speed datacom interconnections over multi-mode fibers (MMFs) for their well-known benefits in terms of cost, testability and consumption. On the other hand, InP VCSELs represent a promising solution to move the same capabilities in other application contexts, where high capacity can be achieved by means of WDM and standard single mode fibers (SMFs) are adopted. These applications, such as enterprise connections, 5G x-haul networks, and MANs, in fact, require single-mode operation to limit the effect of modal and chromatic dispersion, moreover long-wavelength emission in the C band to exploit dense WDM, and high bandwidth to achieve very high transmission rates are required. In the frame of the H2020 project PASSION, InP VCSELs [8,9] sources produced by VERTILAS GmbH have been employed to design and implement a suitable multi-Tb/s TX. These VCSELs show single-mode operation thanks to an appropriate transverse waveguide structure with sidemode suppression ratio higher than 35 dB and a stable polarization output. Long-wavelength emission in the C band is assured by exploiting a buried tunnel junction (BTJ) approach. Moreover, the reduced active area allows an expected far field confined in less than 12° with a structure optimized for massive integration. A short-cavity is obtained by a very short resonator length and optimized active region, guaranteeing high bandwidth (around 18 GHz). The VERTILAS InP VCSEL short-cavity structure and the picture of the samples employed for the PASSION TX are shown in Fig. 1. The exploited InP VCSELs are able to be directly modulated with standard OOK or PAM4 modulation formats, with very low power consumption, less than 30 mW. In order to target at least 50-Gb/s rate per VCSEL with this kind of directly-modulated sources, very effective multicarrier modulation formats, such as OFDM [10,11] and DMT can be exploited. In particular, DMT offers many advantages thanks to bit and power loading, matching the limited modulation bandwidth of the VCSEL and the nonuniform response of the whole communication system [12]. Moreover DMT provides a great flexibility at the DSP level: in case of optical networks, this flexibility allows to optimize the transmitted capacity as a function of losses, transmission impairments (e.g. dispersion, nonlinearities etc.), and traffic patterns.

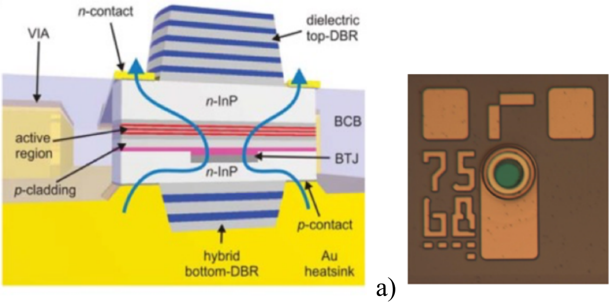


Fig. 1. Short-cavity VCSEL structure optimized for high modulation bandwidth (a) and picture of the VERTILAS ling-wavelngth InP VCSEL (b).

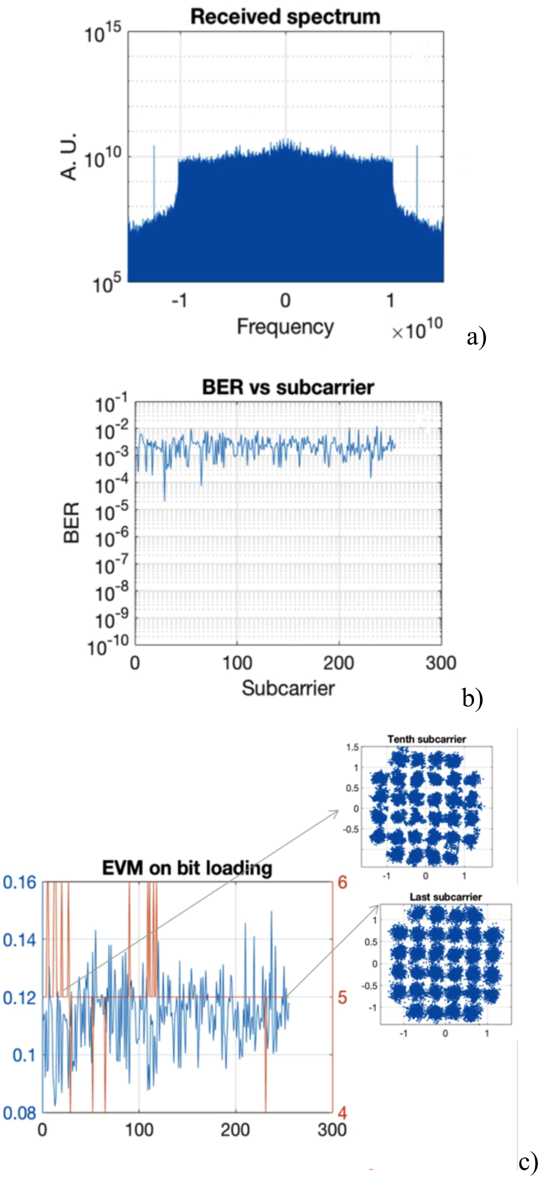


Fig. 2. InP VCSEL DMT modulation: received electrical spectrum (a); BER per subcarrier (b); bit loading and corresponding EVM (c). In the in-sets received constellations for the 10th and 255th subcarrier.

An example is shown in Fig. 2, where more than 50 Gb/s rate is experimentally demonstrated by employing an InP 14-GHz bandwidth VCSEL. The DMT signal is composed by 256 sub-carriers in 10-GHz range, i.e. the sub-carrier spacing is 39.0625 MHz. Directly-modulated DMT allows to obtain up to 50.2 Gb/s targeting a bit error rate (BER) lower than 3.8·10-3, achieving 5-fold improvement of the transmission rate with respect to the electrical modulation bandwidth.

III. Heterogeneous Integration of VCSEL-based TX Module PIC

The well-proven 3-µm SOI photonic integration platform developed in VTT in combination with integrated up-reflecting mirrors and solder coated cavities has been used to achieve the heterogeneous integration [13] of 40 InP VCSELs, such as the ones described in the previous section, and a SOI 40:1 multiplexer PIC, in order to realize an innovative multi-Tb/s TX module. The considered heterogeneous integration of III-V active devices allows to fully exploit both wafer level packaging (WLP) and E/O wafer level tests, scaling up in volume manufacturing while dramatically reducing assembly costs. The 40-VCSEL based TX module constitutes the fundamental building block for the design and realization of the innovative sliceable bandwidth/bitrate variable transceiver (S-BVT) developed in PASSION [14,15]. The 40 integrated InP VCSELs emit in the C band, covering the ITU channels from 19 to 59, with dense WDM spacing of 100 GHz. 50-Gb/s rate is achieved per state of polarization (SOP) per each VCSEL thanks to DMT, in order to target an aggregated capacity per TX module of up to 2 Tb/s.

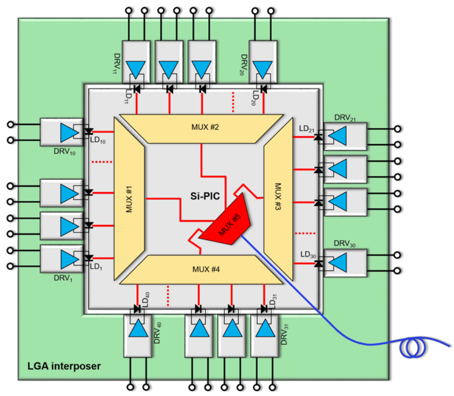


Fig. 3. Scheme od the 40-BVSEL TX module prividing a total capacity of 2 Tb/s.

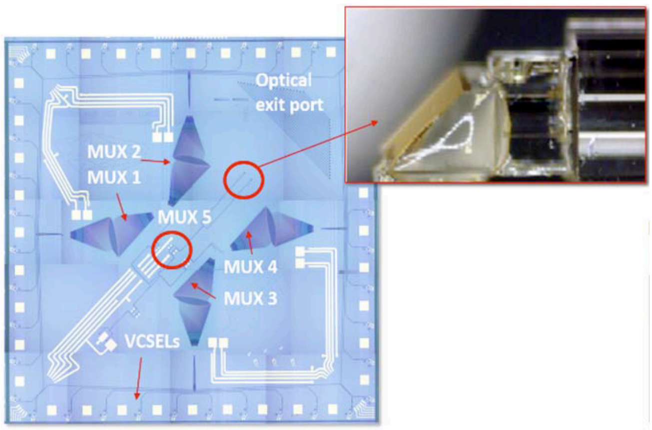


Fig. 4. PIC main layout. In the in-set picture of the up-reflective mirror coupling the outuput SMF.

The TX module scheme combining 40 100-GHz spaced VCSELs is reported in Fig. 3, while the PIC main layout is shown in Fig. 4. Taking in account the channel pitch depending on the dimension of the VCSELs and the linear drivers, the optical PIC size is about 2cmx2cm for a total aggregated transmission capacity of 2 Tb/s.

The SOI PIC includes 4 identical "S" shaped 10:1 arrayed waveguide gratings (AWGs) (MUX 1÷4 in the picture) followed by a 2-stage MZI interleaver (MUX5) realized with a cascade of 3 Mach-Zehnder interferometers balanced by microheaters [16]. All input waveguides are terminated with 45 deg. up-reflective mirrors allowing VCSELs to be flip-chip bonded on top, while coupling their optical beams into SOI waveguides. Similarly, the output waveguide (exit port) of the PIC is terminated with an up-reflective mirror, enabling the vertical tilt of the exit-beam toward a micro-optic, GRIN-based, fiber pigtailed periscope, whose concept is shown in Fig. 5. This special arrangement has been specifically designed to result flat and parallel to the SOI surface of the PIC, overcoming vertical and bulky fiber-block assemblies (such as those used for coupling gratings) dramatically improving the intrinsic reliability and overall form-factor of the module. A picture is visible in the in-set of Fig. 4. The described AWG design has been selected among other multiplexing solutions thanks to its good tolerance during manufacturing processes, and a well-established behavior modeling. On-chip loss (about 1.6 ÷ 0.4 dB) and crosstalk (lower than -20 dB) has been measured. Up-reflective mirrors design, working with total internal reflection (TIR) have been selected for their highest reflection coefficient. Up-reflective mirror coupling-losses when interfacing a SMF has been measured lower than 0.5 dB in both TM/TE polarizations over the entire C-band [17], while total coupling losses of a VCSEL on top of an up-reflective mirror is reported to be 4.4 dB and 4.1 dB, respectively.

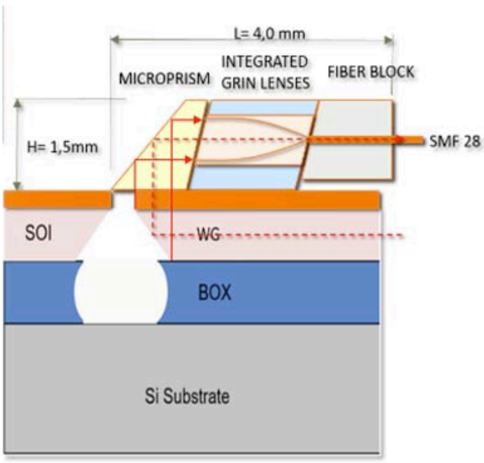
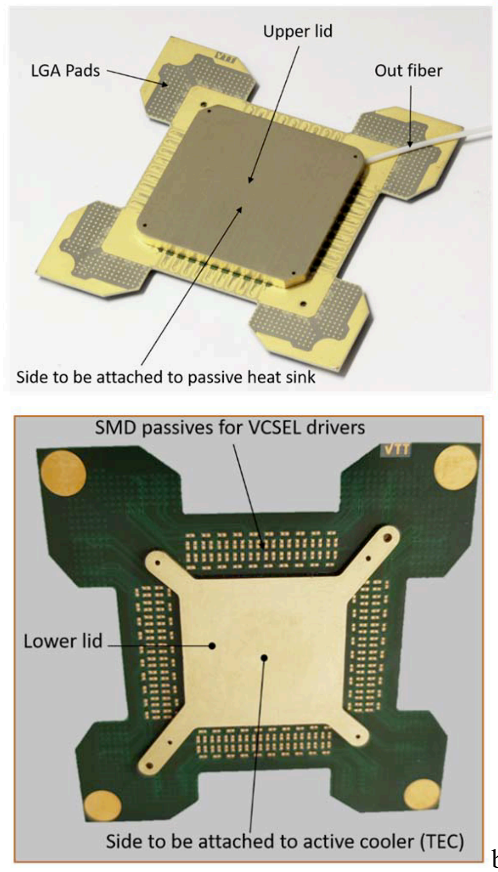


Fig. 5. Periscope-coupling concept.

IV. Multi-Tb/s TX module integration

The TX module PIC requires accurate electrical, thermal and opto-mechanical interconnection solutions overall performed by a single electrical interposer based on a 8 layers 600 μm thick, ENEPIG-finished, Panasonic Megtron7 substrate. The necessary VCSEL drivers characterized by a linear response are flip-chip bonded onto a suitable LGA interposer designed to provide interconnection and thermal decoupling capabilities to the Si-PIC, realizing a very compact, thermally efficient packaging solution. The LGA performs external electrical interconnections, while a re-distribution layer design (RDL) routing 40 × 100 Ω ground-signal-signal-ground (GSSG) differential lines for VCSEL-drivers inputs as well as 648 DC lines (including ground distribution, DC voltage and digital controls) for a total amount of 808 pads has been designed and realized. The fully packaged 40-VCSEL TX module with the LGA interposer, completed with sealed upper and lower lids, is presented in Fig. 6.

Considering the thermal drift of the VCSEL emission wavelength (around 70 pm/°K), an active cooling is implemented by means of an externally-mounted thermoelectric cooler (TEC). To minimize the power consumption, both PIC and VCSELs operate at +40°C ± 0.1°C, achieving a good trade-off between optical output power and TEC dissipated power, in the operating range from -5°C to +70°C. The VCSEL drivers do not require to operate at constant temperature, so their heats are simply dissipated in still air (at max +50°C ambient temperature), through a passive heat sink. To reduce parasitic heat flows moving from the interposer hottest areas (where drivers are mounted) to the silicon PIC, a precise 200 μm thermal insulating air-gap separating the PIC four side edges and the interposer, has been considered.



a)

b)

Fig. 6. VCSEL-based TX module fully packaged with LGA interposer and sealed with upper (a) and lower (b) lides.

Finally, an evaluation board, presented in Fig. 7, suitable to be hosted in a standard ETSI subrack, has been implemented by SM Optics to test and characterize the module in an industrial environment.

V. VCSEL-based TX modular approach

Starting from the TX module described in the paper, constituted by 40 100-GHz spaced DMT-modulated

VCSELs, a super-module TX enabling up to 8 Tb/s total aggregated capacity can be assembled.

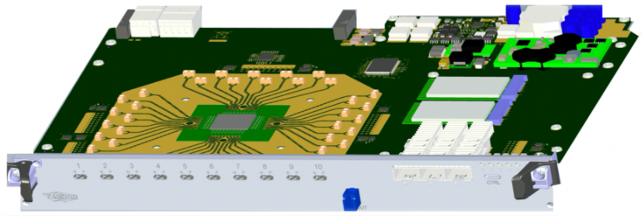


Fig. 7. Evaluation board suitable to ETSI subrack.

In particular, we adopt a modular approach: just identical modules, such as the described one, are designed and developed. The 40 emitted wavelengths from the VCSELs in each module can be fine-tuned in a range of 0-75 GHz through the VCSEL bias current and stabilized by a temperature cooler. Combining 4 of such a module, the full 160-channels TX super-module [18,19] is obtained, characterized by 25-GHz granularity, as shown in Fig. 8. The exploited modularity offers the ability to fabricate and stock only one TX module type and to use the identical 40-VCSEL modules to build the full 160-channel TX super-module. Thanks to polarization-division multiplexing (PDM), 16-Tb/s total capacity can be also achieved for the proposed TX super-module.

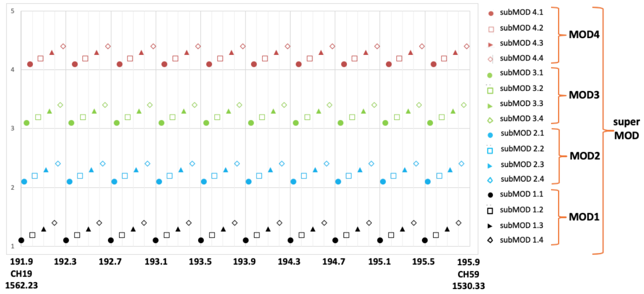


Fig. 8. Grid of the VCSEL emission wavelengths for the 4 TX modules constituting the super-module.

VI. Conclusions

The exploitation of high-bandwidth long wavelength VCSELs, directly, emitting in the C band, allows to design and develop an innovative TX module. The module is realized by means of a SOI platform, with the heterogeneous integration of 40 InP VCSELs with the silicon PIC, scaling up in volume manufacturing and dramatically reducing assembly costs. DMT direct modulation allows to achieve at least 50 Gb/s rate per VCSEL, targeting 2-Tb/s aggregated capacity for the whole TX module, with 40 WDM channels spaced 100 GHz. The same 2-Tb/s TX module can be used to build a super-module targeting up to 8 Tb/s aggregated capacity, by exploiting VCSEL emission wavelengths tuning, and 16 Tb/s by means of PDM. The modular approach guarantees scalability and low cost, low power consumption and reduced footprint. The capabilities of the proposed VCSEL-based multi-Tb/s TX allows to face the request of huge throughput networks, in particular in term of sustainability. Low cost, energy efficiency and reduced footprint are guaranteed by the use of VCSELs as laser sources, of direct modulation, of heterogeneous integration and by the technological solutions adopted in the PIC design and integration. Moreover, the modular approach guarantees also fabrication scalability and stock optimization.

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