Abstract—Single-mode 1.5-μm InP-based vertical-cavity surface-emitting lasers (VCSELs) with a 1.5-λ long semiconductor cavity and two dielectric distributed Bragg reflectors (DBRs) are presented. The electrical, thermal and optical characteristics are studied as a function of tunnel junction diameter and for different temperatures ranging from -10°C up to 65°C. Small-signal modulation bandwidths in excess of 21 GHz at room temperature are demonstrated for a DC power consumption below 10 mW. In this paper, the superior dynamic characteristics of these VCSELs are shown by demonstrating error-free operation at data rates up to 50 Gb/s in back-to-back configuration by non-return-to-zero modulation and without any equalization. Neither forward error correction nor digital signal processing were required.

Index Terms— Vertical cavity surface emitting lasers, InP, optical modulation, semiconductor laser.

I. INTRODUCTION

The annual global amount of data stored, transmitted and processed by individuals and by machines is growing exponentially, and will reach tens of zettabytes by 2020 [1]. Distributed computing, sensor networks, cloud-based services and their users are driving this growth motivating the need for scaling of the capacity of datacom and telecom networks [2].

Directly modulated VCSELs are particularly attractive for high-speed applications due to their cost effectiveness, energy efficiency, and small footprint [3]. Small-signal bandwidths as high as 30.0 GHz and 25.6 GHz have been demonstrated for multi-mode GaAs-based VCSELs emitting at 850 nm and 980 nm, respectively [4, 5]. Compared to their GaAs counterparts, InP-based VCSELs emitting at longer wavelengths (i.e. 1.3 and 1.55 μm) have gained large interest due to the lower power consumption (lower band gap) and ten times lower losses in silica-based optical fibers. In this paper, the superior dynamic performances of the ultra-short 1.5-λ cavity VCSELs presented first in [6] are studied. Before this work, InP-based single-mode VCSELs have demonstrated maximum small-signal bandwidths below 18 GHz [7-9].

A common approach used to boost the intrinsic small-signal modulation bandwidth of semiconductor lasers is the reduction of the laser’s effective cavity length [10]. By means of dielectric DBRs, high refractive index contrast between the lambda-quarter layers is achieved leading to short propagation depths of the field in the mirrors and reducing the overall cavity length [9]. However, the poor thermal and electrical conductivity of dielectric DBRs challenges thermal, electrical and optical properties of these surface-emitting lasers challenging the reduction of the semiconductor cavity length. For InP/air-gap DBRs VCSELs, the higher thermal impedance of the devices with shorter cavities caused an early thermal roll-over which strongly limited the maximum achievable bandwidth [11].

In this work, the stationary and dynamic characteristics of InP-based VCSELs emitting at 1.5 μm with a 1.5-λ long semiconductor cavity and two dielectric DBRs are reported. To the best of our knowledge this is the shortest semiconductor cavity demonstrated for InP VCSELs up to date.

The theoretical background on directly modulated VCSELs is presented in Section II. The electrical, thermal and optical design is introduced in Section III. In Section IV and V, the static and dynamic characteristics of the fabricated lasers are presented and analyzed. This paper is concluded in Section VI.

II. THEORY

The VCSEL’s small-signal modulation response $H(f)$ is a three-pole transfer function given by the combination of intrinsic and parasitic effects [12]:

$$H(f) = \frac{f_R^2}{f_R^2 - f^2 + j \frac{\gamma f}{2\pi}} \cdot \frac{1}{1 + j \frac{f}{f_p}}$$

where $f_R$ is the relaxation resonance frequency, $\gamma$ is the intrinsic damping factor and $f_p$ is the parasitic cut-off frequency.

The relaxation resonance frequency is approximated as [13]

$$f_R \approx D[I - I_{th}]$$

where $D = \frac{1}{2\pi} \sqrt{\frac{\eta_i \alpha v_g}{qV_p}}$. (2)

Here, the bias and threshold currents are represented by $I$ and $I_{th}$, respectively. The internal quantum efficiency is $\eta_i$, $v_g$ is

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the group velocity, \( a \) is the carrier differential gain, \( q \) is the electron charge, and \( V_p \) is the photon density. The damping is related to the relaxation resonance frequency as [13]:

\[
\gamma = K \cdot \frac{\gamma_0}{f_R} + \gamma_0 \text{ where } K = 4\pi^2 \tau_p (1 + \frac{a_p}{a}). 
\]  

(3)

The photon life time, the photon differential gain and the confinement factor are represented with the symbol \( \tau_p, a_p \) and \( \Gamma \), respectively. The damping offset, which is important at low powers, is \( \gamma_0 \). The photon life time is given by [14]:

\[
\tau_p = \frac{L_{\text{eff}}}{v_g \alpha_1 L + \ln \left( \frac{1}{\sqrt{R_{\text{TM}} - R_{\text{BM}}}} \right)} \quad \text{(4)}
\]

where \( \alpha_1 L \) are the internal losses per round trip, and \( R_{\text{TM}} \) and \( R_{\text{BM}} \) are the reflectivity of the top and bottom mirror, respectively. The effective cavity length \( L_{\text{eff}} \) is the sum of the semiconductor cavity length and of the penetration depths of the field in the two DBRs. The latter is defined as the depth at which the optical field appears to be reflected by a fixed phase mirror, and for high refractive index ratio between the DBRs pairs, it approximates the length at which the field energy density falls to \( 1/e \) of its cavity lambda quarter value [15].

One of the approaches used in order to boost the small-signal modulation bandwidth of semiconductor lasers is the reduction of the photon lifetime [10]. In this work, this is accomplished by a short effective cavity length. This approach increases the relaxation resonance frequency and reduces the damping for a given bias current above threshold with the effect of boosting the overall intrinsic bandwidth. The main drawback is the increase in thermal resistance which means that thermal degradation of the output power (roll over) and of the relaxation resonance frequency will be obtained at lower currents limiting the overall intrinsic bandwidth [11]. Another drawback is the increase in the electrical resistance degrading the static performances, due to the higher dissipated power, and degrading both intrinsic and parasitic dynamic behavior.

### III. Design of Ultra-Short-Cavity VCSELS

A schematic image of a VCSEL with two dielectric DBRs is shown in Figure 1. The optical gain is provided by an active region with seven 6.1-nm thick AlGaInAs quantum wells grown with 1.2% compressive strain. The active region is embedded between an \( n \)-doped InP layer and a highly \( p \)-doped AlInAs cladding. Current confinement is achieved by a \( p^-\)-AlGaInAs/\( n^-\)-GaInAs buried tunnel junction (BTJ), which is highly conducting in a circular area with diameter \( d_{\text{BTJ}} \), while current blocking outside this area is obtained by a reverse-biased \( p^+\)n-junction. The tunnel junction is structured by dry chemically removing the \( n^-\)-GaInAs layer and overgrown by an \( n^-\)-InP layer of thickness \( t_{\text{II}}=360 \) nm in order to match the desired cavity length. The overgrown \( n^-\)-InP is gradient-doped from \( 1 \times 10^{17} \) cm\(^{-3} \) to \( 2 \times 10^{16} \) cm\(^{-3} \) in order to minimize the electrical resistance of the InP cladding by maintaining a sub-mA threshold current. The presented VCSELS employ a 5-pairs dielectric outcoupling AlInAs/ZnS DBR and a 3.5-pairs hybrid AlInAs/ZnS-Au bottom DBR with reflectivities of 99.4% and 99.9%, respectively. The bottom DBR has diameter \( d_{\text{BM}} \).

Dielectric DBRs have the great advantage of a large refractive index contrast which reduces the field penetration depth, and therefore also the effective cavity length. A five pairs AlInAs/ZnS DBR alternates five lambda-quarter layers of refractive index 1.34 and 2.29. The calculated penetration depth of the field is 299 nm. For comparison, we notice that the penetration depth of a semiconductor AlInAs/AlGaInAs DBR is ten times larger. However, the dielectric DBR exhibits the disadvantage of low thermal conductivity (one order of magnitude lower than the one of InP) and poor electrical conductivity (electrical insulator).

The heat generated in the VCSEL cavity \( (P_{\text{diss}}) \) flows radially across the overgrown InP, around the DBR, and it is drained out by means of the gold anode which works as an effective heat sink. This three-dimensional problem can be simplified to a one dimensional problem by solving the Fourier law for cylindrical coordinates from which the thermal resistance \( R_{\text{th}} \), defined by the ratio of power and thermal tuning coefficient, is determined to be:

\[
R_{\text{th}} = \frac{\Delta \lambda}{\frac{\Delta P_{\text{diss}}}{\Delta \lambda}} = \frac{1}{2 \pi k r_B} \ln \left( \frac{d_{\text{BM}}}{d_{\text{BTJ}}} \right) \quad \text{(5)}
\]

where \( k \) is the thermal conductivity of the heat spreading layer. As described in Section II, the relaxation resonance frequency is directly proportional to the square root of the current above threshold. Reducing the thickness of the cavity in order to enhance the dynamic performances increases the thermal resistance and the current-induced self-heating limiting static and dynamic performances. The tradeoff between semiconductor cavity length and heat dissipation plays a crucial role in the enhancement of the VCSEL bandwidth.

The dielectric DBRs are electrical insulators. The current injected by the anode flows radially across the VCSEL’s mesa, facilitated by the highly doped current spreading layers. It is...
the flow of the current in the light propagation direction. Unfortunately, higher resistance yields higher dissipated power for a given current which causes higher internal temperature, and lower parasitic cut-off of the VCSELs. In the devices under study, the serial resistance is dominated by the highly resistive p-doped AlInAs layer. The spreading resistance is reduce by placing highly-doped InP layers of thickness \( t_{SL} \) in the minimum of the field.

Both electrical and thermal resistances are reduced by larger diameters of the tunnel junction. The optimum is found in the largest diameter which still supports single mode operation.

The spreading resistance can be reduced by reducing the resistivity or by increasing the thickness of the spreading layer. The first approach can be achieved by increasing the concentration of Silicon donor impurities in the current spreading layer. The second approach increases the overlap of the optical field with the highly-doped current doped layer increasing the free-carrier optical losses. Given fixed optical losses, the lowest electrical resistance is achieved by decreasing the resistivity of the layer and not by increasing its thickness.

### IV. STATIONARY CHARACTERISTICS

Output power and voltage versus current of three 1.5-\( \lambda \) VCSELs with 3-\( \mu \)m, 4-\( \mu \)m, and 5-\( \mu \)m tunnel junction diameters are shown in Fig. 2 (a). The threshold current ranges from 0.7 mA up to 1.3 mA and, as expected, increases with the area of the active region. The overall resistance is 91 \( \Omega \), 58 \( \Omega \) and 46 \( \Omega \) for \( d_{BTJ} \) of 3-\( \mu \)m, 4-\( \mu \)m and 5-\( \mu \)m, respectively.

The overgrow of the structured tunnel junction by solid-source molecular beam epitaxy does not flatten the tunnel junction cylindrical structure, which is reproduced at the semiconductor interface with the bottom mirror. The effect will be an effective fiber-like waveguiding depending on the ratio between the overgrown tunnel junction thickness and the cavity length [16]. Corresponding to the diameter of an optical fiber’s core, the diameter of the tunnel junction will determine how many transverse modes can propagate in the cavity. In Fig. 2 (b), the optical spectrum of three VCSELs biased at 7 mA is presented. Multimode behavior is observed for VCSELs with tunnel junction diameter of 5-\( \mu \)m, while VCSELs with smaller diameters show single-mode operation at room temperature.

Output power and voltage versus current of a 1.5-\( \lambda \) VCSEL at various heat-sink temperatures are shown in Fig. 2 (c). The threshold current ranges from 0.9 mA up to 1.2 mA. By increasing the heat-sink temperature from \(-10^\circ C\) up to \(65^\circ C\), the maximum output power decreases from 3.1 mW to 1.3 mW, and the roll-over current reduces from 10.5 mA to 6.6 mA. The voltage slightly decreases by increasing the temperature.

In Fig. 2 (d), the optical spectrum of the same VCSEL biased at 7 mA is presented for various heat-sink temperatures. Increasing the temperature from \(-10^\circ C\) up to \(65^\circ C\) leads to a strong increase in the side mode suppression ratio. This effect is related with the cavity mode-gain offset. For temperatures equal or higher than \(20^\circ C\), single mode operation is achieved. The targeted wavelength of 1.55 \( \mu \)m was not met due to unintended thin layer removals during the fabrication process.

![Image](image-url)
However, this wavelength mismatch can be compensated by adding an index-matching interposer between the semiconductor cavity and the outcoupling mirror or by including a sacrificial InP layer in the epitaxial design.

In Fig. 3 (a), the differential quantum efficiency (DQE) is presented as a function of the heat-sink temperature for three tunnel junction diameters. Increasing the temperature from -10°C up to 65°C leads to a decrease in DQE from 52% to 37% for a 5µm BTJ diameter.

In Fig. 3 (b), the threshold current is plotted as a function of the heat-sink temperature for three tunnel junction diameters. A minimum threshold current of 0.67 mA has been achieved at room temperature for a 3 µm BTJ diameter.

In order to evaluate the intrinsic parameters of the VCSELs under study, two different top DBRs have been evaporated with reflectivity of 99.38% and 99.79%. The internal losses $\alpha_i$ and the internal quantum efficiency $\eta_i$ are estimated by linear fitting the inverse of the DQE versus the inverse of the mirror losses $\alpha_m$ according to the formula:

$$\frac{1}{DQE} = \frac{1}{\alpha_m} \frac{1}{\eta_i} + \frac{1}{\eta_i}.$$  

The corresponding internal losses and the internal quantum efficiency versus the BTJ diameter are plotted in Fig. 4 (a). The internal losses are the sum of material losses (free-carrier absorption and inter valence-band absorption) and diffraction losses. The diffraction losses increase by decreasing the BTJ diameter [16, 17] due to the fact that the off-axis propagation of the light reduces the reflectivity of the DBR. Unfortunately, the internal quantum efficiency, that is the fraction of terminal current that generates carriers in the active region, decreases with larger tunnel junctions.

Measured and calculated electrical resistances are plotted in Fig. 4 (b) as a function of the inverse of the BTJ area. The overall resistance is the combination between spreading and serial resistance. Large BTJ diameters offer lower electrical resistivity that is also lower Ohmic losses.

The thermal resistance $R_{th}$ is extracted experimentally by calculating the ratio between the power tuning coefficient of the emission wavelength at a constant temperature $\Delta \lambda / \Delta P_{\text{diss}} \mid_{P_{\text{diss}=0}}$ (0.612 nm/mW at 20°C for a $d_{BTJ}=4$ µm) and the thermal tuning coefficient of the same device at a constant dissipated power $\Delta \lambda / \Delta T_{RS} \mid_{P_{\text{diss}}}$ (0.077 nm/K at $P_{\text{diss}=0}$ mW for a $d_{BTJ}=4$ µm).
The results are plotted in Fig. 4 (c) as a function of the natural logarithm of the ratio between back mirror \(d_{BM}\) and tunnel junction diameter \(d_{BTJ}\). The points have been fitted according to Eq. 5 in order to extract the effective thermal conductivity of the thermal spreading layers yielding 48 W/(K m).

V. Dynamic Characteristics

As discussed in Section III, these VCSELs are designed for enhancing the high-speed capabilities of state-of-the-art devices by means of a 1.5-\(\lambda\) short semiconductor cavity length. In the following, only single-mode VCSELs will be studied, namely VCSELs with a tunnel junction of 3 and 4 \(\mu m\) in diameter.

The VCSELs’ small-signal modulation responses were measured with a HP 8510C Vector Network Analyzer and the light was coupled to a \(\eta 7\) photoreceiver module with 40-GHz bandwidth and 150-V/W conversion gain. The \(S_{21}\) parameters of two 1.5-\(\lambda\) VCSELs with 3- and 4-\(\mu m\) tunnel junction diameters are depicted in Fig. 5 (a) for different bias currents. The highest small-signal modulation bandwidth reached with the presented VCSELs is 22 GHz at room temperature (uncooled). This result refers to a 4-\(\mu m\) VCSEL biased at 6.8 mA and with a total DC power consumption of only 8.9 mW. For comparison, wafer-fused long-wavelength VCSELs show state-of-the-art bandwidth of approximately 11 GHz [7].

The presented \(S_{21}\) parameters have been fitted according to Eq. 1 in order to extract intrinsic and parasitic laser parameters. The relaxation resonance frequency versus the square root of the current above threshold is plotted in Fig. 5 (b) for the two VCSELs with 3- and 4-\(\mu m\) tunnel junction diameters. The VCSEL with the 4-\(\mu m\) tunnel junction diameter shows a \(D\)-factor of 10.1 GHz/mA\(^{0.5}\), while the one with the 3-\(\mu m\) diameter has a \(D\)-factor of 12.5 GHz/mA\(^{0.5}\).

According to Eq. 3, the K-factor describes the rate at which the damping increases with the squared relaxation resonance frequency, and is proportional to the photon life time. For the VCSELs with 3- and 4-\(\mu m\) BTJ diameters, the damping versus the squared relaxation resonance frequency is plotted in Fig. 5 (c) and the K-factor is extracted by a linear fit leading to 172 ps and 165 ps for the 3- and 4-\(\mu m\) BTJ, respectively. The K-factor is slightly higher for the smaller diameter. This result can be tentatively explained by the combinations of two different effects related to the strong increase in internal losses for smaller diameters shown in Fig. 4 (a). First, the photon life time increases by increasing the BTJ diameter. Second, the photon density increases by increasing the BTJ diameter. As a consequence of the latest, the gain compression at high photon densities forces the carrier density to increase in order to maintain the threshold gain constant reducing the ratio \(a_p/a\).

The K-factor is related to these two effects according to Eq. 3 explaining the results of our measurements.

Aside from small-signal measurements, large-signal digital modulation experiments are necessary to characterize the performance of the VCSEL in an optical link. A device with a 4-\(\mu m\) BTJ-diameter is biased through a bias-T and driven by a SHF 12100B pulse pattern generator. The coplanar pads of the anode and cathode are probed with a 40 GHz PicoProbe 40A GSG probe. After fiber alignment with 10-\(\mu m\) resolution XYZ-stages, coupling losses between 8 and 9 dB still exist. In order to compensate for these coupling losses, an Erbium-doped fiber amplifier (EDFA) is used in the optical link of which the output power can be altered with a variable attenuator. The receiver chain ends with a 32 GHz linear photo-diode and transimpedance amplifier (DSC-R409) connected differentially to either 50 GHz 86118A remote sampling heads for recording eye diagrams or to the SHF 11100B error analyzer for real-time bit-error rate (BER) measurements.

Captured eye diagrams of back-to-back (BTB) experiments with a pseudorandom bit sequence (PRBS) of \(2^7\)-1 at 28, 40, 50 and 55 Gb/s are shown in Fig. 6. Large signal intrinsic behavior of the VCSEL can be best inspected at 28 Gb/s since bandwidth limitation does not affect the eye opening at this data rate. A small amount of overshooting and a dual transition edge are noticeable. These effects could be minimized by increasing the bias current and by lowering the modulation voltage. However,
this impacts the extinction ratio (ER) and the optical modulation amplitude (OMA) in a negative way. A bias current of 6.8 mA and a modulation voltage of 500 mV peak-to-peak resulted in the best trade-off between these parameters and corresponds to an estimated ER of 8.7 dB and OMA of 5 dBm. According to Fig. 5 (b) and (c), the VCSEL is operated near maximum relaxation resonance frequency. Open eyes are observed up to 50 Gb/s. At 55 Gb/s, severe eye closure occurs due to the VCSELs bandwidth limitation of 22 GHz.

The sensitivity of the long-wavelength VCSEL link can be derived from the BER curves in Fig. 7 (a) and (b). At 28 Gb/s BTB, the link achieves a BER <10^{-12} for input powers larger than -8.7 dBm. Increasing the length of the SMF to 200 m and 1 km results in a power penalty of 1.1 dB and 2.9 dB, respectively. Targeting 40 Gb/s BTB degrades the sensitivity to -5.3 dBm while error-free transmission is maintained at 200 m before chromatic dispersion starts to limit the performance, as is the case for 1 km of fiber. The link is pushed to its limits at 50 Gb/s BTB, given the fact that the remaining power budget is a marginal 1.5 dBm, and is broken at 200 m and at 55 Gb/s BTB. Applying equalization to the modulation signal or adopting for 4-level modulation could restore the power budget or cover longer distances, as demonstrated in [18] with the previous generation of this VCSEL. Energy efficiency, defined as heat-to-data ratio, measures 130 fJ/bit at 50 Gb/s and is on par with the fastest multi-mode VCSEL [4].

VI. CONCLUSION

The static and dynamic characteristics of 1.5-µm InP-based VCSELs with a 1.5-λ long semiconductor cavity length and two dielectric distributed Bragg reflectors have been studied. These devices future the highest small-signal bandwidths demonstrated up-to-date for directly-modulated long-wavelength VCSELs, allowing data rates up to 50 Gb/s without equalization or forward error correction.

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