High-speed optical characterization of intensity and phase dynamics of a 1.55µm VCSEL for short-reach applications

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Abstract: Using sonograms and phase retrieval we experimentally investigate the pattern dependence of the amplitude and phase dynamics, the linewidth enhancement factor, and the chirp of a data-modulated 1.55µm vertical-cavity surface-emitting laser (VCSEL).

OCIS codes: (250.7260) Vertical cavity surface emitting lasers; (120.5050) Phase measurement

1 Introduction

Vertical-cavity surface-emitting lasers (VCSELs) operating at a wavelength of 1.55µm are new and potentially important light sources for optical access applications, such as central-office interconnects, parallel-optical data links or metro-feeders, where they could allow for the low-cost deployment of short reach links [1,2]. At this wavelength standard-single-mode fibers have minimum attenuation and erbium-doped fiber amplifiers (EDFAs) can be used for optical amplification. Due to the lasers' low threshold current and power consumption they are also potential transmitter sources for innovative technologies like integrated optical interconnects on electrical circuit boards, enabling enhanced data rates in backplanes, computers, or server systems [3]. For all these applications it is important to temporally resolve the output of the VCSEL to identify optimal driving conditions and to predict and mitigate degradation from optical fiber transmission impairments.

In this paper we report on the measurement of the intensity and phase dynamics of a directly data-modulated 1.55µm-VCSEL and their pattern dependence using sonograms and phase retrieval. We also calculate the linewidth enhancement factor α and the frequency chirp for different driving conditions and modulation patterns. In contrast to earlier measurements [4], which only quantify the chirp-parameter for sinusoidal modulation at certain output powers, the results presented here perfectly describe the behaviour of the VCSEL under typical operating conditions. The linear approximation of the chirp parameter as a small-signal parameter depends highly on the driving conditions of the laser, thus our complete dynamic characterization leads to a better understanding of the properties of the device.

2 Vertical-cavity surface-emitting laser (VCSEL)

We used a commercially available, pigtailed, uncooled VCSEL with buried tunnel junction (Vertilas) at the wavelength of 1.55µm, rated for 2.5Gb/s modulation but driven at a data rate of 10Gb/s. As shown in the inset of Fig.1a, the coaxial packaged VCSEL was mounted at the end of a 50 Ω microstrip line, in series with a 12 Ω surface mount chip resistor. Such careful laser mounting significantly improved the VCSEL's modulation response at low frequencies (< 5GHz). However, the mounting had no impact on the high-frequency behaviour. Fig.1b presents the small-signal modulation characteristic at 25°C. The insets give back-to-back eye diagrams at data rates of 2.5Gb/s and 10Gb/s. The DC-characteristics are given in Fig.1a, revealing a low threshold current of I_{th}≈0.9mA, a maximum laser output power around 0.8mW, and a slope efficiency of 0.135mW/mA. The linewidth of the VCSEL was measured to be 29MHz. A strong variation of the output wavelength as a function of temperature was observed (cf. inset Fig.1b).

3 Measurement principle

The time-resolved intensity and phase of the output of the VCSEL are obtained by performing phase retrieval on the measured sonogram of the output [5]. When the VCSEL is driven by a periodic pattern, the sonogram of the output is obtained by measuring the intensity of the filtered output after filtering by a spectral filter (0.2 nm bandwidth) with a sampling oscilloscope (30 GHz bandwidth) for various central frequencies of the filter. From the measured $S(\omega,t)$, where ω is the central frequency of the filter and t is the time, the principal component generalized projection algorithm is used to perform phase retrieval. This leads to the electric field of the output E(t) without any assumption. Proper acquisition of the experimental trace is ensured if the intensity is measured over a period of the

electric field and the filter is scanned with steps equal to the inverse of this period, which in our case allowed 8 bit-patterns at 10Gb/s.

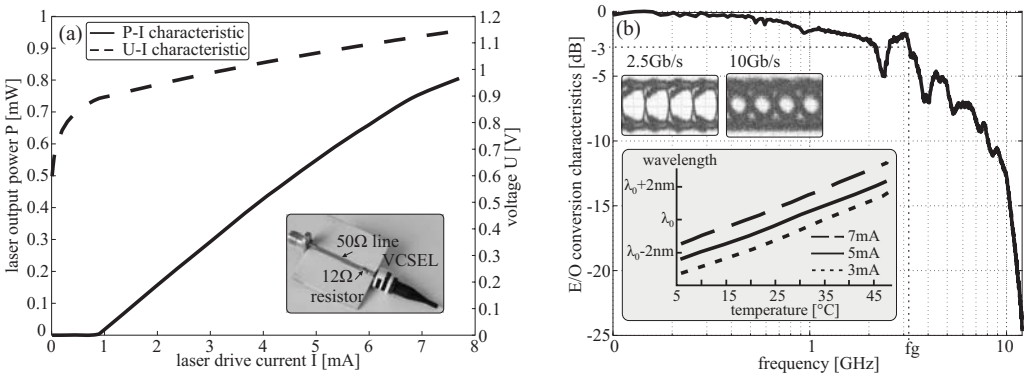

Fig. 1 (a) Output power vs. drive current (solid line) and laser voltage vs. drive current characteristic (dashed line) of the 1.55µm VCSEL at 25°C. Inset: VCSEL mounted on a microstrip line. (b) Small-signal modulation characteristic. Insets: Back-to-back eye diagrams at data rates of 2.5Gb/s and 10Gb/s, and temperature dependence of the wavelength for three bias currents.

4 Experimental results

The linewidth enhancement factor α of a laser is defined as the change in the real part of the refractive index as a function of the change in carrier numbers divided by the differential gain [6]. In a VCSEL, large-signal modulation leads to a phase shift during the transitions of the data signal (transient chirp) as well as to a long-term shift in the laser frequency (adiabatic chirp). An expression for the frequency chirp in terms of output power P(t) is

$$\Delta f(t) = \frac{\alpha}{4\pi}\left(\frac{d}{dt}\ln P(t) + \kappa P(t)\right), \tag{1}$$

where κ is a constant depending on the geometry of the laser, and the optical frequency. In eqn. (1) the first term represent the transient chirp, whereas the second term determines the adiabatic chirp. In the transient chirp limited regions, such as the rising and falling edges, α can be calculated according to [7]

$$\alpha = -2P\frac{d\phi/dt}{dP/dt}. \tag{2}$$

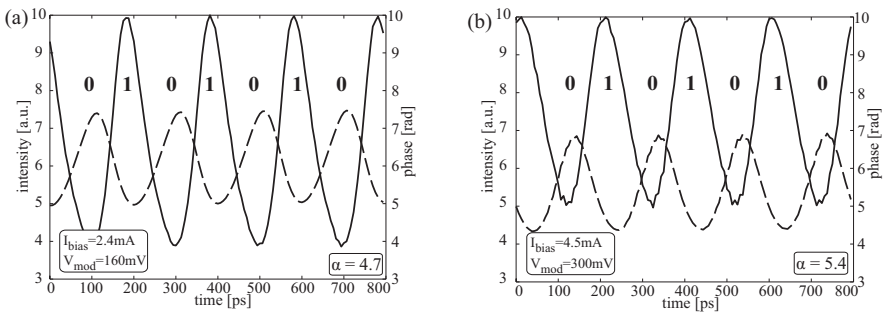

Fig. 2 Intensity (solid line) and phase response (dashed line) of the VCSEL modulated with a "0101010"-pattern at a data rate of 10Gb/s with (a) bias current I_{bias}=2.4mA and modulation swing V_{mod}=160mV and (b) I_{bias}=4.5mA and V_{mod}=300mV.

Figure 2 shows our measurement results for two different driving conditions using a NRZ "0101010"-pattern at a data rate of 10Gb/s as modulation signal. A bias current of I_{bias}=2.4mA and a modulation swing of V_{mod}=160mV lead to an extinction ratio of only 4dB and a linewidth enhancement factor of α=4.7 (cf. Fig.2a). For a larger bias current of I_{bias}=4.5mA and a modulation swing of V_{mod}=300mV (extinction ratio 3dB) α increases to α=5.4 (cf. Fig.2b). These results are in excellent agreement with the α parameter determined from the linewidth-power product [8]. The measurement shows that α depends on the driving conditions and has its minimum values at low optical output powers, i.e. for low bias currents.

4.1 Intensity and phase dynamics

For high-speed applications it is important to characterize the pattern dependence. The chirp parameter is only a simplified description, whereas our measurement technique allows a complete characterization of the device by measuring the intensity and phase of the output. Figure 3 shows the intensity (solid lines) and phase (dashed lines) response of the VCSEL using different modulation patterns at a data rate of 10Gb/s, for two different driving

conditions. From the derivation of the phase response, the frequency chirp Δf (i.e. the frequency difference between "0" and "1") was calculated. It is found that the chirp is higher for low bias currents and modulation swings. Specifically, the chirp for I_{bias} =2.4mA and V_{mod}=160mV is up to 9 GHz higher than for I_{bias}=4.5mA and V_{mod}=300mV (cf. Fig.3). For patterns with a low percentage of zeros the extinction ratio is small, leading to a lower amount of chirp Δf. The measurement of the intensity shows that the turn-on behaviour is improved if the "zero"-level of the modulation signal I_0 is further above the threshold level I_{th}. With increasing I_0/I_{th} the overshoot decreases significantly (cf. Fig.3a and 3b), also strongly affecting the chirp characteristic in this region. Therefore, in communications applications it might be necessary to trade off the amount of chirp (and overshoots) against the effective receiver sensitivity, which decreases at low extinction ratios.

4.2 Transmission of chirped optical pulse

The frequency chirp derived from the phase modulation is positive at the rising edge ($\delta\phi/\delta t < 0$) and negative at the falling edge ($\delta\phi/\delta t > 0$), thus leading to a negative chirp parameter C. Such a chirp variation should lead to further broadening of the pulse when propagating in a medium with a positive dispersion parameter D. This is confirmed by our measurement results shown in Fig.3c, where a single pulse from the VCSEL was transmitted via a standard single mode fiber (SSMF) with a total dispersion of 238 ps/nm or via a dispersion compensated fiber (DCF) with an accumulated dispersion of -296 ps/nm. Propagation through the DCF clearly led to a compression of the pulse width and an enhancement of the peak power, whereas after the SSMF the pulse was significantly broadened.

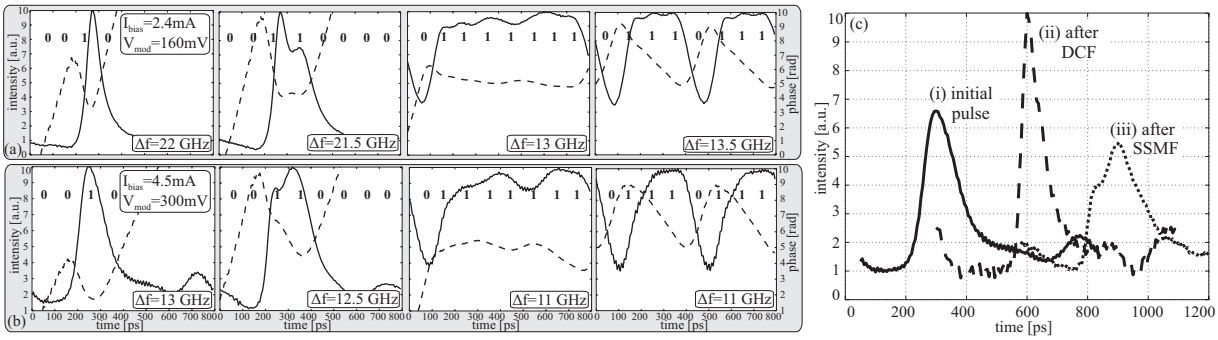

Fig. 3 Pattern dependences of the intensity (solid lines) and phase (dashed lines) response including the measured chirp in GHz (Δf is the frequency difference between "0" and "1") for (a) I_{bias}=2.4mA and V_{mod}=160mV and (b) I_{bias}=4.5mA and V_{mod}=300mV. (c) Transmission of a single pulse from the VCSEL over two different fibers. (i) Pulse at input facet, (ii) compressed pulse after propagation over a DCF with CD=-296ps/nm and (iii) broadened pulse after propagation over a SSMF with CD=238ps/nm.

5 Conclusion

We have experimentally investigated the intensity and phase characteristics of a 1.55µm VCSEL. Different driving conditions, modulation patterns and fiber types were considered in our study. From the measurement of the linewidth enhancement factor and the pattern dependent chirp behaviour, and considering the low optical output power, it becomes clear that for high data rates the investigated VCSEL with buried tunnel junction might only be suited for short reach link applications. The impact of chirp within optical communication systems using this type of VCSEL sources could be minimized using electronic equalization (EDC) [9], forward error correction (FEC) [9], or negative dispersion fibers [10].

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