Chirp Based Direct Phase Modulation of VCSELs for Cost-Effective Transceivers

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A 2.5Gb/s DPSK transmitter based on direct phase modulation of a VCSEL using its own chirp is proposed. The VCSEL, which wavelength is 1539.84nm, has been characterized both static and dynamically. The sensitivity of a single photodiode heterodyne receiver using the proposed 2.5Gb/sVCSEL transmitter is -39.5dBm. Thus, this transmitter is an extremely cost-effective solution for future access networks.

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The traffic demand over access networks is growing exponentially due to cloud computing based new services, the Internet of Things (IoT) and the convergence between wireless and optical communications in the new 5G paradigm [1]. Flexible ultra Dense Wavelength Division Multiplexing (uDWDM) Metro-Access Networks using coherent detection are a promising solution for these convergent networks [2] but cost-effective transmitters have to be designed for a better development and deployment of these networks. In recent years, some cost-effective devices have been proposed, as directly phase modulated Reflective Semiconductor Optical Amplifiers (RSOA) [3, 4], with or without remote pumping, and directly phase modulated Distributed Feedback lasers (DFB) [5, 6] or intensity modulated Vertical Cavity Surface Emitting Lasers (VCSEL) [7]. In addition, VCSELs have been tested as Local Oscillators (LO) for heterodyne receivers [4, 7]. VCSELs can reduce the transceiver cost for access networks because they are potentially the cheapest lasers that can be fabricated, and phase modulation may provide the power budget needed to deploy cost-effective transceivers.

In this letter, we present a direct phase modulation of a VCSEL through the chirp of the laser. First, we have obtained its static and dynamic parameters (frequency chirp) and used them to simulate its behavior and modulate its phase. A 2.5Gb/s Differential Binary Phase-Shift Keying (DPSK) has been achieved, and it has been demodulated by coherent heterodyne reception.

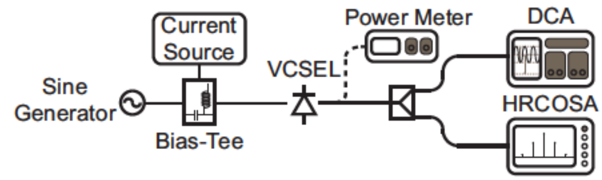

Fig. 1. Experimental setup for the VCSEL characterization.

The static and dynamic (frequency chirp) parameters of a commercially available VCSEL from Raycan™ with thermal stabilization have been measured . The measured static parameters are the lasing threshold, the slope efficiency and the wavelength and optical power in terms of the bias current and temperature.

The VCSEL static parameters have been obtained setting the VCSEL in continuous emitting mode and varying the bias current and the temperature using the setup shown in Fig. 1. The laser threshold, the slope efficiency and the emitting power in

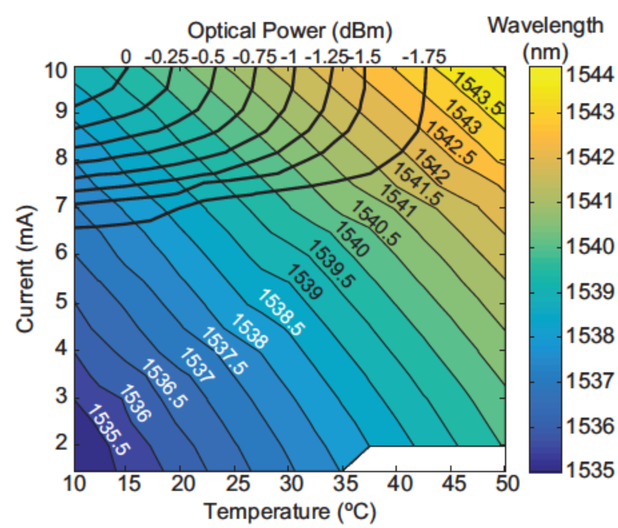

Fig. 2. VCSEL wavelength and constant power curves in terms of the bias current and the temperature.

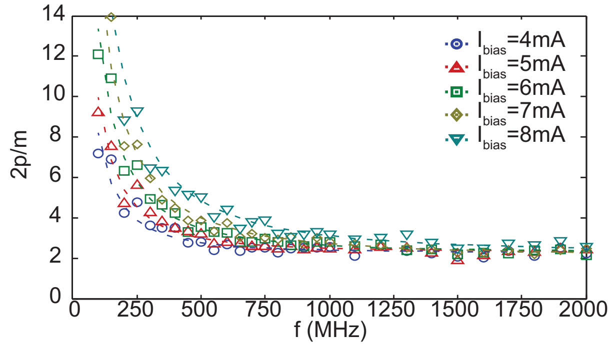

Fig. 3. Experimental 2p / m curves for different bias current.

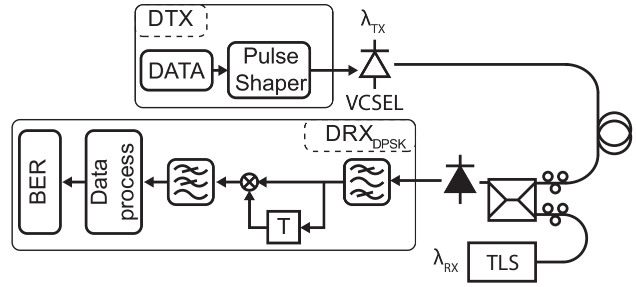

Fig. 4. Experimental setup of the proposed transmitter with heterodyne coherent reception.

terms of the bias current and the temperature are measured with a Power Meter, while the wavelength is measured using a High Resolution Complex Optical Spectrum Analyzer (HRCOSA).

The lasing threshold is 1.399mA and the slope efficiency is 0.137mW / mA, both at 25°C. The emitted wavelength in terms of the bias current and the temperature is shown in Fig. 2. The variation of the wavelength with the temperature is -0.122nm / °C and with the bias current is 0.527nm / mA. In Fig. 2, the constant emitting power lines have been plotted in terms of the temperature and the bias current. The emitted wavelength can be tuned maintaining a constant optical power, in such a way that, for example, a wavelength variation of 5nm can be obtained with a constant emitting optical power of -1.5dBm. Therefore, the emitted wavelength and optical power of the VCSEL can be tuned adjusting both the temperature and the bias current.

The VCSEL dynamic parameter measured is the frequency chirp, defined as the dynamic shift of the operating optical frequency of the laser with the variation of the emitting optical power and, for modulation frequencies higher than the thermal response of the device. It can be described as [8]:

$$\Delta\nu\left(t\right) = \frac{1}{2\pi}\frac{d\phi\left(t\right)}{dt} = \frac{\alpha}{4\pi}\left(\frac{1}{P\left(t\right)}\frac{dP\left(t\right)}{dt} + \kappa P\left(t\right)\right) \quad \textbf{(1)}$$

where $\Delta\nu\left(t\right)$ is the optical frequency shift, $\phi\left(t\right)$ is the instantaneous optical phase and $P\left(t\right)$ is the instantaneous optical power. The transient chirp (α) is associated with the variation of the emitting optical power and the adiabatic chirp (κ) is related with the instantaneous emitting optical power. This parameters have been characterized using the FM / AM method [9, 10] which is based on the measurement of the residual phase to amplitude modulation when modulating a VCSEL with a sine signal of frequency (f) and a low intensity modulation depth (m). The optical intensity output is:

$$I\left(t\right) = I_0(1 + m\cos(2\pi f t)) \quad with \quad m \ll 1 \quad \textbf{(2)}$$

The optical carrier (with power I_0) and the two first order sidebands (I_{+1} and I_{-1})) found in the spectrum are measured employing the HRCOSA while the (m) is measured using a Digital Communication Analyzer (DCA) Oscilloscope, as can be seen in Fig.1. The average optical power of the first order sidebands ($\bar{I}_{\pm1}$) allows to obtain the ratio between residual phase modulation and amplitude modulation ($2p / m$) [8, 9]:

$$\bar{I}_{\pm1} = I_0\left(\tfrac{m}{4}\right)^2\left[1 + \left(\tfrac{2p}{m}\right)^2\right] \quad with \quad m \ll 1, p \ll 1 \quad \textbf{(3)}$$

This ratio ($2p / m$) is related with α and κ [8]:

$$\frac{2p}{m} = \alpha\sqrt{1 + \left(\frac{f_c}{f}\right)^2} = \alpha\sqrt{1 + \left(\frac{\kappa}{2\pi f}I_0\right)^2} \quad \textbf{(4)}$$

where f_c is the chirp frequency, which is the frequency when both chirp effects are equal [11].

In Fig. 3, the ratio $2p / m$ versus the modulation frequency for different bias current (I_{bias}) is shown. The $2p / m$ ratio decreases with the modulation frequency and it converges to the α value when the second factor under the square root of Eq.(4) tends to zero, i.e. at high modulation frequencies. The f_c and the α are obtained adjusting the experimental values to Eq. (4). The f_c increases lineally with the bias current and it is used to obtain the κ factor through the relation shown in Eq. (4). The α and the κ parameters are independent with the bias current. The α parameter is found to be 2.24 ± 0.1 and the κ parameter is $7.6 \pm 0.8GHz / mW$.

The measured dynamic (frequency chirp) parameters are used to simulate the chirp and phase behavior and to develop a DPSK transmitter based on a directly phase modulated VCSEL.

The experimental setup used to obtain a Non-Return-to-Zero (NRZ) DPSK transmitter based on a directly phase modulated VCSEL with an heterodyne receiver is shown in Fig. 4. Data have been encoded differentially in order to use a cost-effective receiver, but the transmitter can use non-differential encoding. The VCSEL is a commercially available device from Raycan^{TM} with thermal stabilization, exhibiting a relatively wide linewidth, higher than 10MHz, and an electrical bandwidth of 4GHz. The VCSEL is biased to a current of 8mA and emits -1dBm optical power at 25°C. The thermal wavelength tuning of this VCSEL, previously described, allows a flexible wavelength allocation.

The pulse shaper for the VCSEL direct phase modulation consists of a sharp transition at the start of the symbol and an exponential decay after the symbol, which can be modeled with first order high-pass function with a cut-off frequency of 636.32MHz and is shown in Fig. 5(a), where we have used a bit rate of 1.25Gb/s for a better description of the chirp and phase behavior. The optical power signal (Fig. 5(a)) is distorted because of the Arbitrary Waveform Generator (AWG) electrical response and the VCSEL dynamic behavior.

This optical power signal has been acquired and used as the input for simulating the chirp of the VCSEL applying the parameters obtained previously. Fig. 5.(b) shows the frequency shift caused by the two terms of the Eq. (1). The first term (transient chirp) is related with the variation of the optical power and the α parameter and shows strong peaks and a small decay

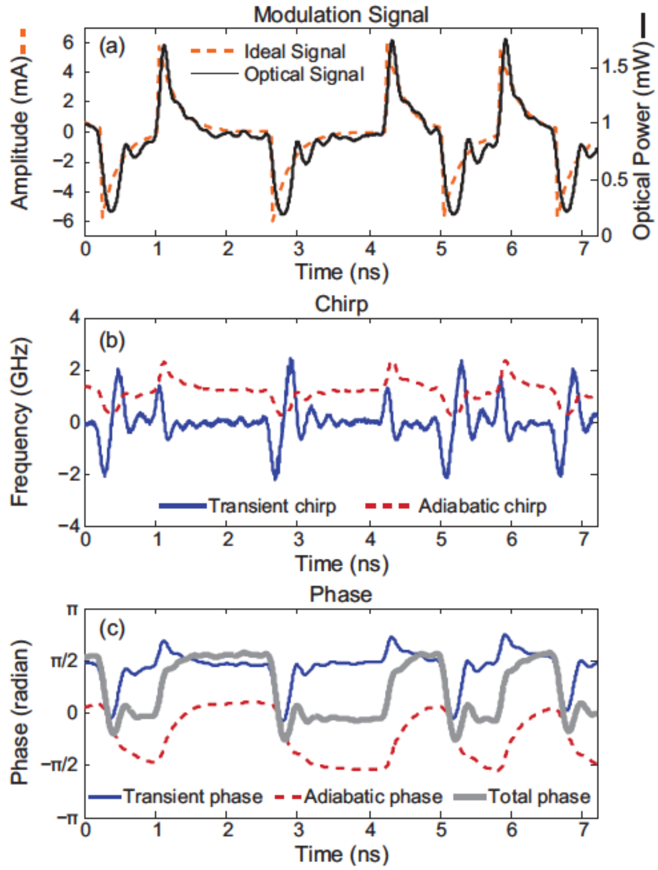

Fig. 5. (a) 1.25Gb/s ideal pulse shaping modulation signal and measured optical signal, Simulated: (b) Transient and Adiabatic chirp, (c) Total phase and the generated phase by the transient and adiabatic chirp.

after it when the sharp transition happens. The second term (adiabatic chirp) is related with the value of optical power and the κ parameter. This second term of the chirp follows mainly the modulation signal.

The optical phase variation generated by the laser frequency chirp is calculated from the integral of the frequency chirp equation (Eq. (1)) and shown in Fig. 5(c). The optical phase change related with the transient chirp shows a sharp transition at the start of the symbol and then an exponential decay, similar to the modulation signal. The optical phase variation due to negative modulation pulses is stronger and sharper than that generated by the positive pulses, because they cause stronger transient chirp frequency shifts producing asymmetrical phase transitions. The optical phase change related with the adiabatic chirp presents a slow slope showing a charging capacitor behavior that contributes to the final value of the phase change. As both optical phase terms happen simultaneously, the total optical phase behavior is also asymmetrical. This can be seen in Fig. 5(c) as an undershoot at the start of the negative pulses.

Different optical phase variations can be obtained by a tight control of the amplitude and the exponential decay of the modulation signal. Therefore, different phase shift keying (PSK) modulation schemes over a directly modulated VCSEL can be achieved. In this paper, we have implemented a 2.5Gb/s DPSK transmitter using just a direct modulation of the VCSEL. This value is near the maximum achievable transmission rate for this

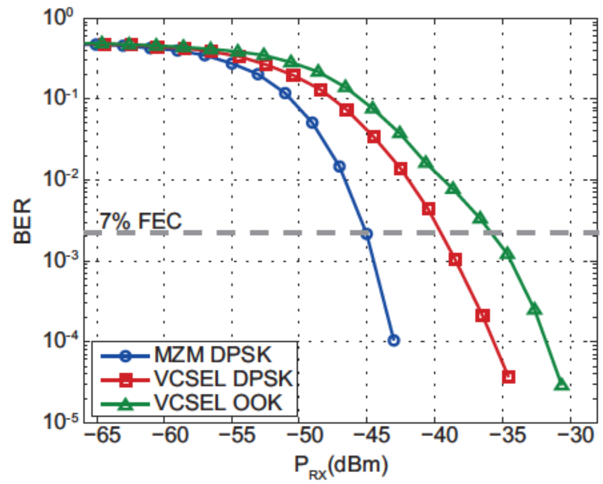

Fig. 6. BER versus received power for the MZM with DPSK, VCSEL with DPSK, VCSEL with OOK for btb scenario.

laser taking into account the modulation signals needed to produce the phase modulation and the 4GHz bandwidth of the device.

The receiver side for the detection of the generated signal is based on a heterodyne receiver with a single photodiode and a external cavity Tunable Laser Source (TLS) as LO with a linewidth smaller than 100kHz and 0dBm emitted optical power. This heterodyne receiver can be upgraded to a polarization independent receiver employing the technique described in [12]. The optical frequency of the LO is tuned 5GHz away from that of the transmitter. In our experimental setup, the polarization of both signals (receiver signal and LO) were adjusted using manual polarization controllers. The received signal is electrically amplified and digitalized with a 40GSa/s Digital Signal Oscilloscope. After the digitalization, the signal is bandpass filtered with a FIR filter in order to reduce the noise as in [4]. Then, the signal is delayed one symbol and multiplied by itself for the DPSK case. Finally, it is low-pass filtered with another FIR filter to demodulate the data.

The results of the 2.5Gb/s DPSK employing a directly phase modulated VCSEL are shown and compared with a 2.5Gb/s DPSK implemented using a Mach-Zehnder Modulator (MZM) and a TLS as the optical source and with a 2.5Gb/s On-Off Keying (OOK) transmission implemented using this same VCSEL. In this later case, the receiver has to be modified after the first FIR filter to demodulate the received signal. The comparison is done in terms of spectrum shape and sensitivity, which is defined as the minimum received power below BER=$2.2 \cdot 10^{-3}$ i.e. the 7% overhead FEC limit to ensure a BER of 10^{-12} [13].

Fig. 6 shows the sensitivity of the three modulation formats in a back-to-back (btb) scenario. The proposed directly phase modulated VCSEL sensitivity is -39.5dBm. The DPSK over a MZM has a sensitivity of -45dBm. Therefore, the proposed transmitter has a power penalty of 5.5dB in comparison with the best performance transmitter (MZM with a TLS as laser), which is a reasonable power penalty for the cost reduction obtained. The OOK using a VCSEL shows a sensitivity of -35.75dBm, which means that the proposed transmitter improves the sensitivity in 2.75dB. This improvement is achieved because the symbol distance is doubled in the phase modulation (DPSK) with respect to the intensity modulation (OOK).

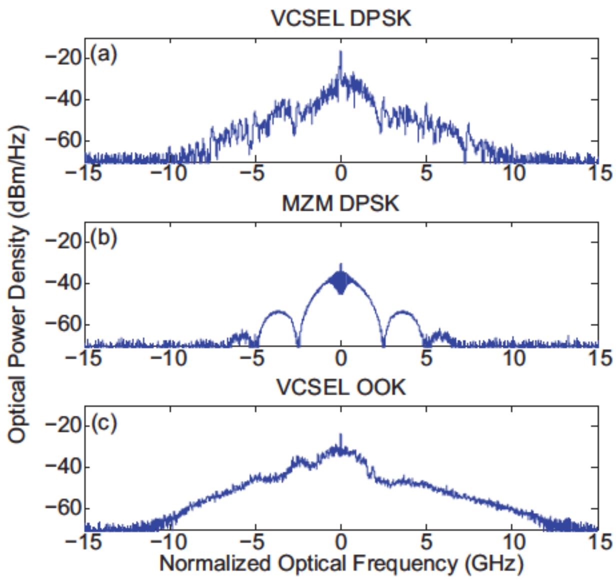

Fig. 7. Optical Spectra for 2.5Gb/s DPSK with VCSEL (a), for 2.5Gb/s DPSK with MZM (b) 2.5Gb/s OOK with VCSEL (c). The central frequency corresponds to 1539.84nm.

The measured penalty of DPSK VCSEL sensitivity for 50Km of Single Mode Fiber (SMF) transmission is below 0.1dB.

Fig. 7 shows the optical spectra of the three compared signals obtained with a HRCOSA. The spectrum of 2.5Gb/s DPSK implemented with our directly phase modulated VCSEL is shown in Fig. 7(a). It has a sinc shape, typical of the NRZ signals, with suppressed carrier, characteristic of the DPSK signals. The spectrum of 2.5Gb/s DPSK over a MZM (Fig. 7(b)) has similar shape and suppressed carrier. The DPSK with MZM has a clearer shape than the DPSK directly modulated with a VCSEL because of the residual amplitude modulation in the later generated by the modulation pulse shape in the VCSEL. The spectrum of 2.5Gb/s OOK over a VCSEL (Fig. 7(c)) has been widened with respect to the phase modulated signal and the optical carrier nearly suppressed because of the uncontrolled chirp effect. Therefore, the utilization of a directly phase modulated VCSEL allows to reduce the employed optical spectrum.

The experimental optical phase eye diagram and optical IQ diagram obtained with a HRCOSA are shown in Fig. 8. The optical phase eye diagram (Fig. 8(a)) shows the phase modulation varies approximately between 0 and π as it is expected for a binary DPSK. The phase variation has been optimized to obtain the minimum BER, which is achieved through a phase shift close to π and the lowest penalty due to the residual amplitude modulation. Variations of the amplitude and the decay of the modulation signal will allow to change the modulation levels in order to obtain higher order modulation (M-PSK).

The experimental IQ diagram (Fig. 8(b)) shows a continuous phase modulation of the VCSEL because the signal is transiting around the unity circle of the IQ diagram. The transition between symbols does not match with the IQ unity circle, as can be seen in Fig. 8(b), due to the residual amplitude modulation. Nevertheless, this residual amplitude modulation is small enough to obtain the desired DPSK signal.

In conclusion, this letter presents the static and frequency chirp characterization of a VCSEL and, for the fist time to the

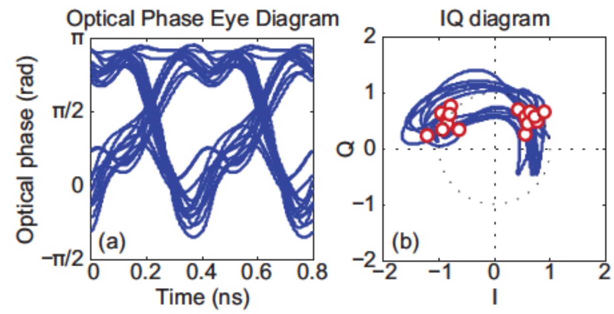

Fig. 8. 2.5Gb/s DPSK with a directly phase modulated VCSEL. Experimental optical: (a) Phase eye diagram, (b) IQ diagram.

best of our knowledge, the VCSEL utilization as phase modulation transmitter using its own chirp parameters. The directly phase modulated VCSEL is employed to develop a 2.5Gb/s DPSK cost-effective transmitter. The 2.5Gb/s VCSEL transmitter is used to obtain a sensitivity of -39.5dBm with a single photodiode heterodyne receiver. The sensitivity of the directly phase modulated VCSEL has only a 5.5dB power penalty compared to a 2.5Gb/s DPSK over MZM and a sensitivity improvement of 2.75dB in relation to the 2.5Gb/s OOK VCSEL. In addition, the 2.5Gb/s DPSK VCSEL has promising characteristics such as: transmitter tuneability by bias and temperature control, narrow spectrum and good quality optical phase eye diagram. All these facts make this transmitter as a promising cost-effective candidate for access networks.

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