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VCSEL Based Optoelectronic Oscillator (VBO) for 1.25 Gbit/s RZ Pulse Optical Data Generation

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***Abstract*— We present the implementation results of a VCSEL based optoelectronic oscillator (VBO) in terms of phase noise and time jitter in the electrical and optical domain. The electrical signal at 1.25 GHz is used as a clock for Non-Return-to-Zero (NRZ) data generation. A system for optical pulse data generation to obtain duty cycles (DC) lower than 30% is proposed and simulated.**

***Keywords*— duty cycle, NRZ, phase noise, pulse width, VBO, VCSEL.**

I. Introduction

In recent years, telecommunications systems, as well as computer systems, face infrastructure challenges to support the increasing data flows. Service providers have deployed networks using optical fiber, coaxial cable and radio links. Many of these systems employ high-frequency signals as carrier signals, synchronization patterns or in data generation (pulse shaping). Just to mention a few: the frequencies for incoming mobile communications 5G (60 GHz band [1]), the eleven study bands (from 24.5 GHz to 86 GHz) for International Mobile Telecommunications IMT 2020 [2] and the high bit rates (200 and 400 Gbit/s) over optical networks using modulation formats like PAM-4 and PAM-8.

Due to the high spectral purity and reduced phase noise of the generated signals, optoelectronic systems are an alternative for microwave generation. The optoelectronic oscillator (OEO) proposed by S. Yao and L. Maleki [3] has a high configuration flexibility, it can be implemented in a wide variety of versions with different optical and electrical components to optimize its performance. In 2007, the VCSEL based optoelectronic oscillator (VBO) was presented [4]. It directly modulates a Vertical Cavity Surface Emitting Laser (VCSEL) taking all the advantages of this kind of lasers. The highest frequency reported for the VBO is 10 GHz using the optical injection locking technique [5].

Optoelectronic oscillators have been used in different telecommunication link segments. For clock recovery, some injection locked OEOs have been used for line-rate and pre-scaled clock recovery and signal format conversion [6]. Other implementations have allowed to change the encoding format (from Non-Return-to-Zero NRZ to Return-to-Zero RZ) at 40 Gbps using 3 intensity modulators [7].

Although transfer rates are currently high, there are still applications where the transfer rate is around 1 Gbps. This is the case of outdoor Optical Wireless Communication (OWC) also known as Free Space Optical (FSO). Until today, some FSO links tested employ different modulation formats and low transfer rates. For instance, in [8] a 622 Mbps download link was implemented using 4-pulse position modulation (4-PPM) between the Optical Ground Station OGS and NASA's Lunar Atmospheric and Dust Environmental Explorer (LADEE). For inter-satellite communications, [9] shows the results obtained of a 1.2 Gbps link (BPSK homodyne detection) and [10] presents the experimental results of Return-to-Zero On Off Keying (RZ-OOK) and RZ Differential Phase Shift Keying (RZ-DPSK) modulations at 1.25 Gbps.

In this paper we present a system for optical pulse data generation at 1.25 Gbps using a VCSEL based optoelectronic oscillator. The second section presents the VBO architecture and a mathematical model for the phase noise prediction. The results of the implementation and analysis of phase noise and random jitter are presented in section 3. Finally, some conclusions are presented.

II. VCSEL Based Optoelectronic oscillator VBO

In a VBO, see Fig. 1, a mono-mode VCSEL is directly modulated to produce microwave signals. The highest frequency of the system is given by the laser bandwidth. The frequency of the generated signal is given by the cutoff frequency of the band-pass filter (BPF).

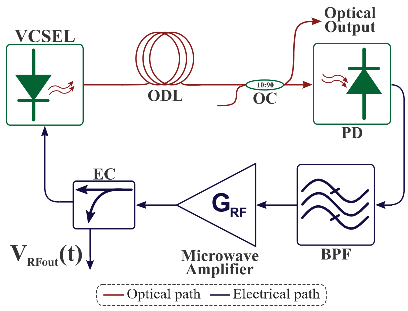

Fig. 1. VCSEL Based Optoelectronic Oscillator Setup

The noise generated by the photodetector (PD) is filtered and amplified to modulate the VCSEL. The optical carrier is transmitted through an optical delay line (ODL) to the photodetector. The electrical and optical signals are obtained by adding an electrical (EC) and optical coupler (OC), respectively.

A. Phase noise response

The phase noise of the VBO can be modeled by means of the linear feedback system proposed by Rubiola [11] for delay-line oscillators. In the system (see Fig. 2), the signals correspond to the propagation of the phase fluctuations of the optoelectronic oscillator components.

If the noises generated by the optical and electrical elements are uncorrelated, the power spectral density ($S_\Psi(s)$) of the noise is the sum of the noise contributions of the different elements referred to the impedance load of the microwave amplifier (Z_A).

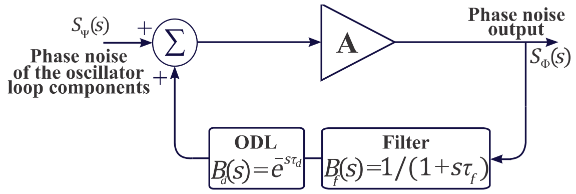

Fig. 2. Phase noise model of VBO

Considering the photodetector shot noise, the relative intensity noise of the VCSEL (RIN_{VCSEL}), the phase variations in the optical fiber due to Rayleigh diffusions (RIN_{fiber}) and the thermal noise current, $S_{\Psi}(s)$ can be expressed as (1) [5].

$$S_{\Psi}(s)=\left[\left(RIN_{VCSEL}+RIN_{fiber}\right)i_{ph}^{2}+2qi_{ph}+\frac{4k_{B}T}{R_{ph}}\right]*Z_{ph}\|Z_{A} \quad (1)$$

where i_{ph} is the photodetected current, k_B is the Boltzman constant, T is the operating temperature and Z_{ph} is the photodetector impedance.

Finally, using theory of linear feedback systems, the power spectral density of phase noise $S_{\Phi}(s)$ can be expressed according to (2).

$$S_{\Phi}(j\omega)=\left|\frac{1}{1+B_{d}(j\omega)B_{f}(j\omega)}\right|^{2}*\left(S_{\Psi}(j\omega)+S_{amplifier}(j\omega)\right) \quad (2)$$

where $S_{amplifier}$ corresponds to the power spectral density of the microwave amplifier noise.

B. Time jitter

Time jitter is the timing variations of signal transitions from their ideal occurrence [12]. For the VBO, the jitter is analyzed in the electrical and optical domain. In the electrical case, the main contribution of noise is given by the thermal and shot noises [13] and other non-correlated noise sources. The root mean square RMS of the jitter is calculated from the phase noise according to (3) [14].

$$\sigma_{RMS}=\sqrt{\int_{-\infty}^{+\infty}S_{\Phi}(f)df}=\frac{1}{2\pi f_{R}}\sqrt{2\cdot\int_{f_{\min}}^{f_{\max}}\mathcal{L}(f)df} \quad (3)$$

where f_R is the resonance frequency, f_{min} and f_{max} are the boundaries of the frequency ranges, and $\mathcal{L}(f)$ the phase noise expressed in linear units.

For the optical domain, the jitter is associated to the turn-on delay due to the large modulation of the VCSEL. The turn-on delay t_{on} is the time in which the photon number grows from the laser threshold (S_c) to the high state (S_{on}) [15]. The jitter is defined as the standard deviation t_{on} probability density function (PDF).

III. Results

For the VBO implementation, pigtailed VCSELs in C and O-band were used. The oscillation frequency was determined by a microwave cavity filter with a central frequency of 1.25 GHz and a 3dB bandwidth of 3 MHz. The optical fiber length was varied between 1 and 2 km to verify the reduction in phase noise and random jitter (RJ) of the electrical signal generated. Also, the bias current of the VCSEL was modified from 5 to 9 mA to validate the effect of RIN noise on phase noise, random jitter and optical pulse width.

A. Phase noise measurements

All the phase noise measurements were made applying the direct measurement method (electrical spectrum analyzer). Fig. 3 shows the phase noise at 10 kHz offset for a 1.25 GHz VBO when 1 and 2 km spools were used, and the bias current was 7 mA. For this linear polarization point, it can be observed how the phase noise improves when the ODL length increases since the length is directly related to the quality factor Q of the resonant cavity. Due to the non-chromatic dispersion of the optical fiber in O-band, the phase noise is improved.

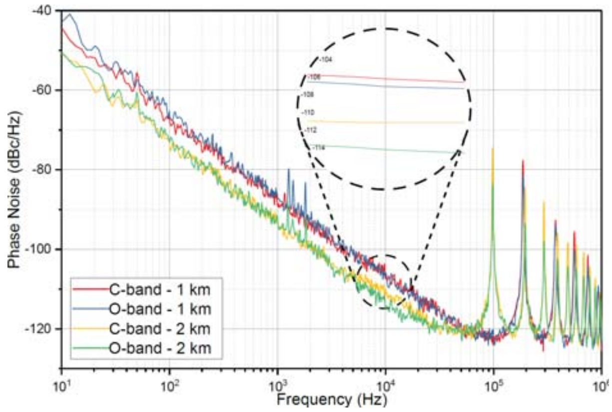

Fig. 3. Phase noise measurements for the 1.25 GHz VBO

Fig. 4 summarizes the results when the bias currents of the VCSELs were changed. For this implementation, the best phase noise (-114 dBc/Hz @10kHz) was achieved when the bias current was 7 mA, an ODL of 2 km and an O-band VCSEL were used. At the same time, it can be observed that for each optical band and a different optical delay line length, the phase noise evolves following the same pattern. In this way, the relationship between the phase noise and the RIN of the VCSEL described in (2) is verified.

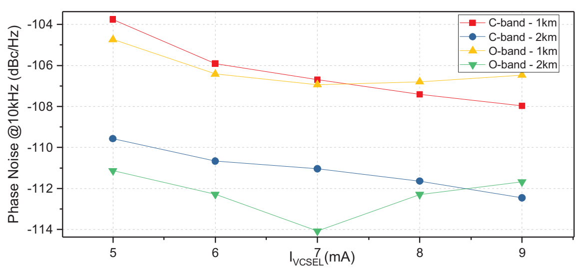

Fig. 4. Phase noise for all VBO implementations

In C-band, the best result was obtained when the polarization current was 9 mA (-112.5 dBc/Hz). This polarization point is close to the saturation point (10 mA) and corresponds to the lowest RIN. In addition to the zero dispersion of the optical fiber, the RIN, leads to the reduction of phase noise when lasers in the C-band are used.

B. Random Jitter of the electrical signal generated

According to (3), the jitter of the electrical signal can be determined with the area under the curve of the phase noise.

Using this mathematical approach, the random jitter was determined for each case of implementation using an integration range from 10 Hz to 1 MHz. Fig. 5 shows the random jitter behavior when the bias current changes.

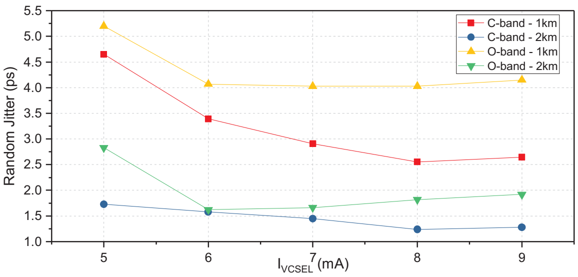

Fig. 5. Random jitter of electrical signals generated

As expected, the lowest RJ (1.24 ps) is achieved when the ODL is 2 km, due to its relation to the phase noise. However, the lowest results are obtained using VCSELs in C-band, and not with O-band (lowest phase noise). One of the possible causes is the difference in RIN between the two lasers bands.

A useful mechanism to identify the RJ sources is the direct measurement of jitter spectrum. With this measure it is possible to know the frequency in which the jitter is generated and apply the corrective measures.

C. *Random jitter and pulse width of the optical pulses generated*

The optical pulses characteristics widely depend on the VCSEL RIN and the optical fiber dispersion. Table I shows the results of the RJ measured directly with an oscilloscope. The lowest RJ (9.28 ps) is obtained in C-band, due again to the difference of lasers RIN. The random jitter behavior, for each band, follows the same pattern considering that the only difference is the dispersion added when the ODL length increases.

TABLE I. RANDOM JITTER OF OPTICAL PULSES

I_{VCSEL} (mA)	***C-band – 1 km***	***C-band – 2 km***	***O-band – 1 km***	***O-band – 2 km***
5	*10.42*	*10.57*	*12.27*	*12.76*
6	*9.62*	*9.93*	*11.39*	*11.65*
7	*9.5*	*9.88*	*10.62*	*10.96*
8	*9.31*	*9.68*	*12.43*	*12.75*
9	*9.28*	*9.52*	*13.37*	*14.18*

The pulse width is measured according to the full width at half maximum (FWHM) definition. Fig. 6 shows the optical pulses when the current was 7 mA. The pulse width (PW) is related to the optical fiber dispersion. In O-band, PW is 92.9 ps with 1 km ODL. PW increases by 2 ps when ODL is 2 km due to fiber dispersion effect. This phenomenon is strongest in C-band, going from 93.7 ps to 97.6 ps, an increase of 3.9 ps.

Using the FWHM definition, it is possible to determine the positive duty cycle (DC). For the thinnest pulse (ODL = 1 km in O-band), the duty cycle is of 11%. This value is below the values that can be obtained with two MZM intensity modulators for RZ-OOK [16]. For this duty cycle, the phase noise and RJ of the electrical signal and RJ of the optical pulses could be improved. For this reason, a trade-off must be reached between the relationship of pulse width, phase noise and random jitter.

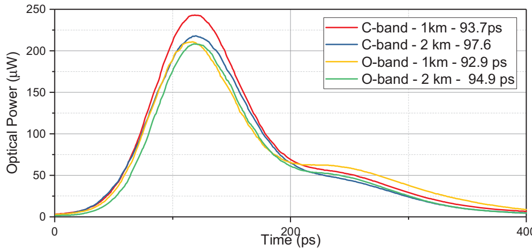

Fig. 6. Optical pulses generated at 7 mA.

D. *NRZ-data generation*

To validate the VBO operation, the electrical signal at 1.25 GHz was used as clock input of a pseudo random binary sequence (PRBS). The bit rate was 1.25 Gbps and the pattern length was 2^7- 1. The ODL length was 2 km, the bias current was 9 mA for a C-band VCSEL. The results were compared with the results obtained when the PRBS uses its own clock.

Fig. 7 presents the phase noise and RJ of two clocks used. In both cases, the clocks have spurious modes and a similar stability. The PN is slightly better for the VBO (-113 dBc/Hz) and the RJ is slightly better on the PRBS clock (1.31 ps).

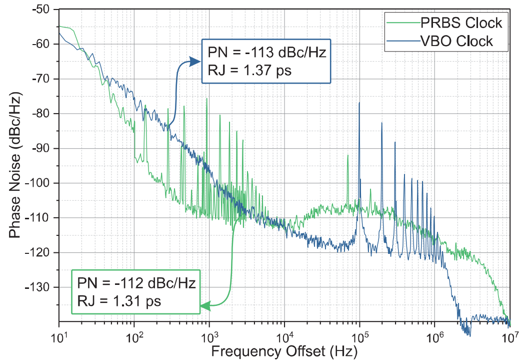

Fig. 7. Phase noise of VBO and PRBS clock.

The RJ spectrum was measured to identify the RJ sources in the generated data. Fig. 8 presents the RMS magnitude of the random jitter for two clocks. In both cases, there are spectral lines spaced at an interval that is the inverse of the pattern length.

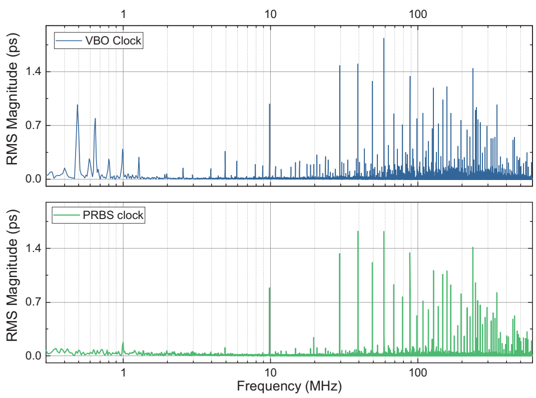

Fig. 8. RMS jitter of VBO and PRBS clock.

The total random jitters were 1.75 ps (VBO) and 1.7 ps (own clock). The RJ is greater for the VBO due to the spurious modes generated by the ODL (frequencies below 1 MHz). As shown in section B, to decrease the RJ you must increase the ODL length and to use a higher bias current (for C-band VCSELs) and a filter with a narrow bandwidth.

For the data generated with the VBO, the total jitter (TJ) peak-to peak @BER 10^{-12} is 72 ps and the eye opening is 0.91 UI (Unit Interval). This value is within the Gigabit Ethernet 1000BASE-T standard.

E. Optical pulse data generation

The optical pulses (low duty cycle) and the clock signal generated by the VBO can be used for the optical data generation according to the proposed scheme of Fig. 9.

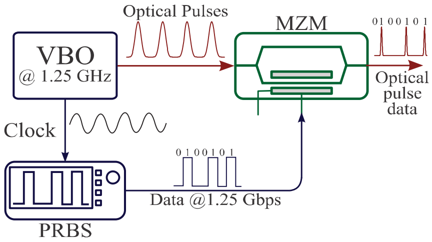

Fig. 9. Proposed scheme for optical pulse data generation.

The system was co-simulated using Matlab® and VPIphotonics Design Suite™. The optical pulses were generated in Matlab. Their DC was adjusted between 10% and 50%. With these results, the need for a phase shifter between the NRZ signal and the optical pulses was identified.

In a next stage, the system must be implemented in C-band considering that it is the optical band for FSO. The pulsed optical data must be characterized in terms of total jitter, extinction ratio (ER) and pulse width.

Because the bit rate of the system is limited by the VCSEL bandwidth, it is possible to use on-chip VCSEL or additional techniques such as injection locking that allows to increase the laser bandwidth (e.g. 10 GHz) and to reduce the RIN noise [5].

IV. Conclusions

In this article, the results of the VBO implementation were presented when VCSELs in C and O-band and different ODL lengths were used. In each case, the bias currents were modified to verify the effect of the RIN on the phase noise and the random jitter of the generated electrical and optical signals.

Regardless of the optical band used, it is demonstrated that the RIN reduction, through the bias current, improves the frequency stability of the electrical signal. Another alternative to improve phase noise is using O-band VCSELs due to the non-chromatic dispersion of the optical fiber. Unfortunately, the RIN in O-band is higher than in C-band, and consequently, the optical pulses and the electrical signal have higher random jitter, limiting their use in telecommunications applications. A trade-off must be made to improve the optical and/or electrical signal.

The optical pulse width is also related to the optical fiber length and the laser band. In O-band the pulses are thinner thanks to the optical fiber, although they have a higher random jitter because of the RIN.

The electrical signal was used as a clock for data generation. The VBO phase noise and the random jitter can be improved to reduce the random jitter of the data generated. The proposed system eliminates an intensity modulator for RZ-OOK modulation and allows reducing the DC of less than 30%. This system is attractive for FSO transmissions due to the optical and electrical signals can be used in the generation and synchronization process.

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