O-band and C-band VCSEL Based Optoelectronic Oscillator (VBO) for 1.25 Gbit/s Pulsed RZ-OOK and RZ-DPSK Free Space Optical Transmissions

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Abstract— In this article, we propose the generation of a microwave signal through a VCSEL Based Optoelectronic Oscillator (VBO) for free space communication applications. This system is implemented using VCSELs in the O-band and C-band. The signals generated at 1.25 GHz and 2.49 GHz are used to produce experimentally Return-to-Zero On Off Keying (RZ-OOK) and Return-to-Zero Differential Phase Shift Keying (RZ-DPSK) modulations for free space optical communication.

Keywords— VCSEL, VBO, OOK, DPSK, RZ, C-band, O-band, free space communication, optical modulation.

I. INTRODUCTION

Due to the growing needs of users, the telecommunications sector had to face representative challenges. Regardless of the user type, the main problems correspond to the development of new technologies and the improvement of others. For example, optical communication links between satellites and ground stations undergo perturbations due to the propagation of the laser beam through the atmosphere. Although several studies and experiments have demonstrated the feasibility of such optical links [1], researches are still needed to identify technical solutions adapted to the specific constraints imposed to these high-speed links (up to 1 Tb/s for telecom applications) to ensure the required level of performance. While radio-frequency transmissions need a breakthrough to solve the bandwidth saturation, optical technologies need to be further developed to exploit its wide bandwidth.

Many telecommunication systems require high-frequency signals that can be used as carrier signals, synchronization patterns or in data generation. An alternative to microwave signal generation systems are optoelectronic systems. These systems improve the performance of the transmission systems due to the high spectral purity and reduced phase noise of the generated signal. One important architecture is the optoelectronic oscillator (OEO) proposed by S. Yao and L. Maleki [2]. Its structure uses electronic and optical components that can be modified to obtain signals with different characteristics regarding their quality, resonance frequency and applicability. An OEO modification was introduced in 2007 [3]. In this case, the optical modulator is removed and a directly modulated Vertical Cavity Surface Emitting Laser (VCSEL) is used. The VCSEL Based Optoelectronic Oscillator (VBO) reduces the cost of implementation, the weigth of the system and energy consumption.

Due to its spectral purity, the narrow circular beam for direct fiber coupling, single longitudinal mode operation and linearity, the VCSELs are used in Microwave Photonics [4]. In [5] the authors used an VCSEL and the Injection Locking technique to increase the effective bandwidth up to 12 GHz, while in [6] implemented a VBO oscillator using VCSEL-by-VCSEL injection locking.

This paper presents the results of microwave signals generation from a VBO oscillator and its integration into a satellite telecommunications application. In the second section, we present a context on free space communications, the third section describes the VBO oscillator and presents the results of implementation at 1.25 GHz and 2.49 GHz. The fourth section describes the transmitter architecture and finally, the experimental results are shown in fifth section.

II. CONTEXT AND MOTIVATION

For the radio-frequency communication through the atmosphere, several constraints and limitations remain unsolved as the saturation radio-frequency bandwidth or low information transmitted rate during the communication.

The design of a free space communication link (see Fig. 1) must quantitatively consider all relevant effect and establish a link budget which incorporates all relevant contributing factors to reliably predict the performance of the space link.

The principal aim of this study is to consolidate optical communication architectures using different modulation formats including duty cycles to increase data rate. Recently, demonstrations have proven the feasibility of optical communication at low bit rate. 622 Mbit/s has been tested using 4-pulse position modulation (4-PPM) between Optical Ground Station OGS, and NASA's Lunar Atmospheric and Dust Environmental Explorer (LADEE) [7]. Alternatively, 10

Mbit/s using OOK modulation between a Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO) [8].

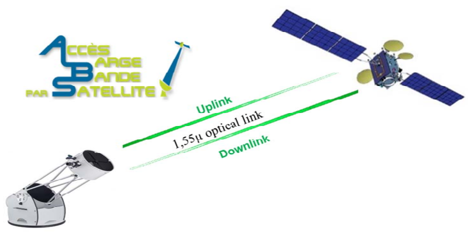

Fig. 1. Free Space Optical Transmission Application

The free space communication links need high frequency signals to obtain different modulation formats. These signals can be generated from oscillators such as VBO. This oscillator is suitable for satellite applications due to its lower power consumption. Our interest is to integrate the design of free space communication links with the generation of microwave signals using OEOs and to verify their performance in telecommunications applications

III. VCSEL BASED OPTOELECTRONIC OSCILLATOR

A. VBO architecture

The VCSEL based Optoelectronic Oscillator [3] is a variation of OEO proposed by S. Yao and L. Maleki [2]. The VBO configuration is shown in Fig. 2. The main difference between the two oscillators is the use of a VCSEL laser directly modulated with the RF amplifier signal. The oscillations are initiated by the noise generated by the photodetector that is filtered and amplified. This signal modulates the optical carrier that is photodetected to produce a microwave signal. The signal is then filtered, amplified and returned directly to the VCSEL, creating a self-sustaining oscillation.

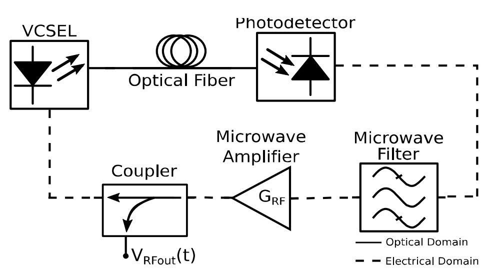

Fig. 2. VCSEL Based Optoelectronic Oscillator Setup

This type of oscillator, in addition to the advantages of VCSEL lasers, is less expensive, smaller and requires lower operating current than other implementations. For this reason, the VBO is attractive for satellite applications.

B. 1.25 GHz and 2.49 GHz VBO Implementation

1.25 GHz and 2.49 GHz VBO oscillator were implemented. For each frequency, RayCan pigtailed VCSEL in O-band and C-band (bands defined by International Telecommunication Union – ITU [9]) were used to verify the effect of the chromatic dispersion.

The optical fiber delay line length was varied using 1 km and 10 km optical fiber spools. The mode spacing in the optical fiber is known as Free Spectral Range (FSR). The delay line length (L) is directly related to the quality factor of the resonant cavity and the FSR is inversely related with L.

A tunable filter at 1.25 GHz and a microwave cavity filter tuned at 2.49 GHz with narrow bandwidth were used to select an oscillation mode. Finally, a 38 dB gain microwave amplifier is used to compensate the loop losses and guarantee a closed loop gain of 1dB.

The phase noise of the generated signals was measured using direct measurement method through an electrical spectrum analyzer. The phase noise allows to determine the oscillator stability in the frequency domain. Fig. 3 shows the phase noise for 1.25 GHz VBO when different lasers (C and O-band) are used.

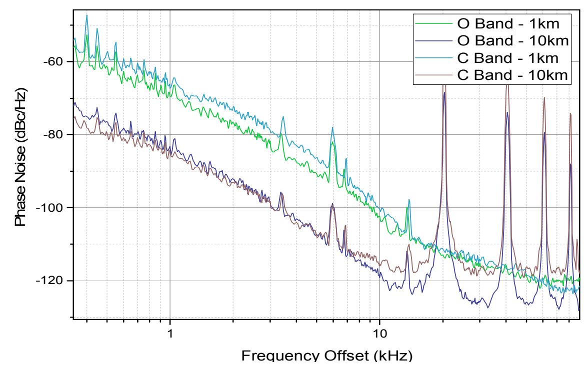

Fig. 3. Phase noise measurements for the 1.25 GHz VBO

Fig. 3 shows that the best phase noise is achieved when the fiber length is 10 km and the wavelength is in the O-band due to the non-chromatic dispersion of the optical fiber. In both bands, it is demonstrated that the phase noise is improved when the optical fiber delay line is enlarged because the Q factor increases. Lower phase noise is obtained with the 2.49 GHz cavity filter. The tunable filter at 1.25 GHz generates noise that impairs oscillator stability. Table I summarizes the measured phase noise for the VBO at 1.25 GHz and 2.49 GHz.

TABLE I. MEASURED PHASE NOISE FOR THE VBO

		Phase Noise (dBc/Hz @10kHz)	
Frequency	***Spectral Band***	***1 km***	***10 km***
1.25 GHz	*O-band*	-102.8	-118.5
	C-band	-100.5	-115
2.49 GHz	*O-band*	-113.2	-127
	C-band	-112	-123.4

IV. OPTICAL TRANSMITTER ARCHITECTURES

For the transmitters, the data used is generated by a Pseudo Random Binary Sequence (PRBS) of length 2^7-1. This signal drives a Mach Zehnder Modulator (MZM1) to convert data in an optical signal. A second modulator (MZM2) is used as a pulse carver which controls the duty cycle of the pulses. The originality of this transmitter is instead to use the signal generator, we use the signal generated by the VBO oscillator to drive our pulse carver and is used as clock signal for the PRBS. Fig. 4. shows the different components assembled.

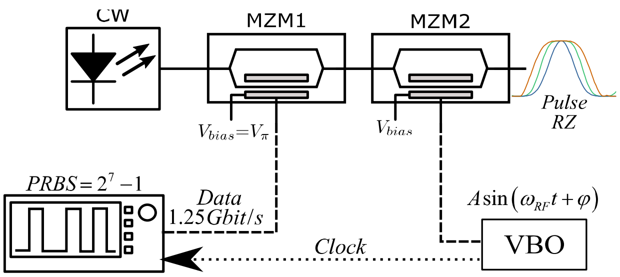

Fig. 4. RZ-OOK transmitter

The transmitter is developped using an optical link software to test the advantages of the RZ-OOK transmitter architecture in a controlled environment. For that, three pulses with duty cycle of 50%, 67%, and 33% were obtained. In all cases, the first MZM was set up in quadrature operation point .

The differences in the duty cycle were achieved setting up several values on the amplitude and phase of the signal generated by the VBO oscillator, and configuring different values in the Bias of the MZM. This MZM is also set up in quadrature operation point.

For example, to generate a 50% duty cycle, the signal of the VBO has a frequency of 1.25 GHz. In this case, the amplitude of this signal is set up in a value which equals to the bias voltage on the second MZM. To change the duty cycle to other, it is necessary to adjust the amplitude of the signal generated by the VBO and its frequency (doubling the amplitude and half of 1.25 GHz).

The results obtained allow us to verify the operation of the RZ-OOK transmitter architecture. The above provides a strengthened basis for the real implementation of the design, and it will permit to contrast the differences between them.

V. Experimental Development

In order to generate a 50% duty cycle RZ-OOK, the VBO at 1.25 GHz and a PRBS at 1.25 Gbit/s were used. To ensure correct modulation, the data and RF signal were amplified and the bias voltage of each MZM modulator was $V_{\pi/2}$. The Fig. 5. shows the results obtained when the band laser and the optical fiber delay line were changed.

Fig. 5 shows the different cycles obtained experimentally. The duty cycle closest to 50% was obtained with the lowest phase noise VBO. In this case the duty cycle was 46.9%, the phase noise was -118.5 dBc/Hz (@ 10 kHz offset), the VCSEL is in O-band and the optical fiber length is 10 km. Analogously, the worst duty cycle (43.6%) was obtained when the phase noise was -100.5 dBc / Hz.

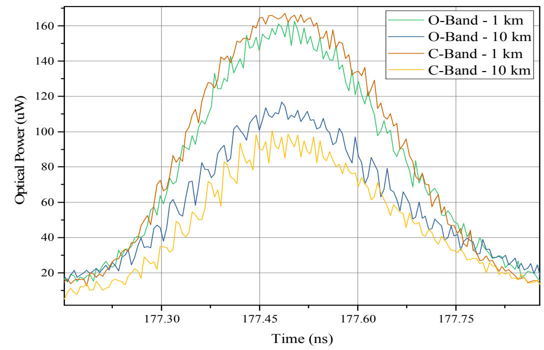

Fig. 5. 50 % RZ pulses duty cycle

When a C-band VCSEL is used, the generated RZ data is affected by phase noise. Fig. 6. shows the eye diagrams when the optical fiber length is 1 km (Fig. 6. a.) and 10 km (Fig. 6. b.). These results show the relationship between the VBO stability (phase noise) and the generated RZ data.

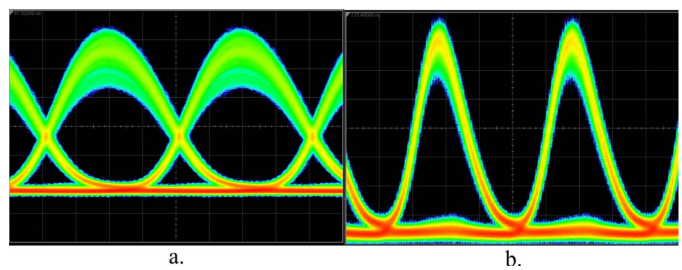

Fig. 6. RZ pulse eye diagrams generated when the optical fiber length is a. 1km. b. 10 km.

To generate pulses with a 33% and 67% duty cycle a 625 MHz oscillator must be implemented. To improve the transmitter and taking into account that the VBO phase noise at 2.49 GHz exceeds those obtained at 1.25 GHz, it is proposed to increase the bit rate to 2.5 Gbit/s and to implement two oscillators with frequencies of 1.25 GHz and 2.5 GHz using microwave cavity filters. This improvement is the next step in this investigation.

VI. Conclusions

A free space optic communication transmitter was implemented using a VBO oscillator to generate the microwave signal. The stability of the oscillator is related to the optical fiber delay line length and the VCSEL wavelength. The best results are obtained with an O-band laser and a longer optical fiber. The non-chromatic dispersion of the optical fiber in O-band allows improving the stability in the frequency domain.

The RZ pulse duty cycle generated is related to the microwave signal quality generated with the VBO. The RZ pulse duty cycle generated with a lower phase noise oscillator is closer to the desired duty cycle and the eye diagram shows that the pulses maintain their amplitude.

The experimentation shows the results compatibility with simulation regarding generated pulses. The simulation results remains ideal comparing with experiment because of phase shift between data signal and the VBO signals or synchronization problems. This comparison study is done using RZ-OOK modulation and it will be interesting to use the RZ-DSPK modulation that improves the receiver sensitivity by 3 dB.

Due to its low power consumption, its operation near the desired point, and its stability, the architecture of the RZ-OOK transmitter proposed, arise as a good candidate to establish a free space communication link.

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