2.49 GHz Low Phase-Noise Optoelectronic Oscillator using 1.55μm VCSEL for Avionics and Aerospace Applications

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Abstract—We present here a 1.55 μm single mode Vertical-Cavity Surface-Emitting Laser (VCSEL) based low phase-noise ring optoelectronic (OEO) oscillator operating at 2.49 GHz for aerospace, avionics and embedded systems applications. Experiments using optical fibers of different lengths have been carried out to obtain optimal results. A phase-noise measurement of -107 dBc/Hz at an offset of 10 kHz from the carrier is obtained. A 3-dB linewidth of 16 Hz for this oscillator signal has been measured. An analysis of lateral mode spacing or Free Spectral Range (FSR) as a function of fiber length has been carried out. A parametric comparison with DFB Laser-based and multimode VCSEL-based opto-electronic oscillators is also presented.

I. INTRODUCTION

The generation of spectrally pure microwave signals has been an important research field for a long time. The need for high performance, high functionality, small package size, low power consuming and low priced oscillators has never been greater. The most demanding applications can be in aerospace and avionics industries where the environment is harsh and the compactness, size and power consumption of a component are critical to the system design. Optoelectronic oscillators (OEO) have been used to generate spectrally pure microwave signals for quite some time now. This class of oscillators uses a distributed feedback (DFB) laser to generate a spectrally pure microwave signal. A directly modulated DFB laser used in the OEO configuration can hence be used as a stable local oscillator (LO) in a number of aerospace and avionics applications. This however comes at the cost of system compactness and renders the system expensive. The objective of this paper is to demonstrate the feasibility of using a 1.55 μm single-mode vertical-cavity surface-emitting laser (VCSEL) in a ring OEO. A comprehensive parametric comparison between optoelectronic ring oscillators using three different optical sources i.e. DFB lasers, 850 nm multimode VCSELs and 1.55 μm VCSELs is also presented.

II. PRINCIPLE

The VCSEL-based oscillator (VBO) is a subclass of optoelectronic oscillators (OEO) that use VCSELs as the principal optical sources for the generation of high spectral purity microwave signals, in lieu of DFB lasers. The conception of such a microwave signal generation testbench
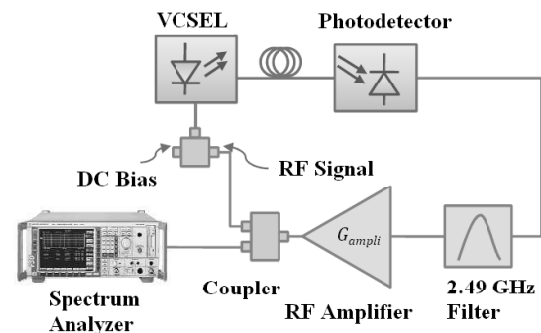

Fig. 1. 1.55 μm single-mode VCSEL based oscillator testbench.

is suggested in [1]. The testbench chosen to realize the VBOs is based on a looped configuration. The loop consists of a VCSEL, a fiber-roll that acts as a delay-line, a photodetector that performs optical to electrical transformation, a bandpass filter centered on the frequency f_0 and an amplifier with a gain G_{ampli}.

The underlying principle of this OEO is the assumption that the output of an intensity-modulated laser carries a spectrally pure microwave signal whose frequency is equal to the laser modulation frequency. The conception of such an OEO can therefore be separated into two different phases. During the first phase that we would call the open-loop configuration of the system, the modulating signal is conceived. This is attained by amplifying the system noise and then filtering it to achieve the desired frequency signal. During the second phase of operation, the system functions in the closed-loop configuration. The output of the open-loop configuration, i.e. the modulating signal generated by amplifying various system noise sources, is fed back to the laser as modulating signal hence effectively closing the loop. This two step conception allows the creation of the modulating signal from system noise hence effectively eliminating the need to use an external modulator. The optical output from the intensity-modulated laser is then converted to electrical form using a photodetector and observed on an Electrical Spectrum Analyzer (ESA).

III. PHENOMENOLOGICAL APPROACH

A. General Expression

The expression for the open-loop gain of this opto-electronic oscillator can be written as:

$$\tilde{G}_{OL} = \tilde{\alpha}_E \cdot \tilde{G}_{ampli} \cdot \tilde{\alpha}_o \cdot \tilde{S} \cdot R_{ph} \cdot \tilde{F} \cdot \eta_d \cdot \frac{h\nu}{q}$$
$$\cdot \; \frac{1}{R_d(I)\big|_{I=I_{pol}}} \cdot H_{VCSEL}(\omega)\big|_{\omega=\omega_0} \quad (1)$$

Where

$$H_{VCSEL}(\omega) = \frac{\omega_R^2}{\omega_R^2 + \omega^2 + j\omega\gamma} \quad (2)$$

is the transfer function of the VCSEL.

The electron charge, VCSEL quantum efficiency, the Planck's constant and the VCSEL operation frequency corresponding to the emission wavelength are represented by q, η_d, h and ν. $R_d(I)$ and R_{ph} denote the VCSEL dynamic resistance and the photodetector load resistance respectively. $\tilde{\alpha}_E$ and $\tilde{\alpha}_o$ represent the electronic and optical loop losses respectively, where $\tilde{\alpha}_o$ is equal to $\alpha_o e^{-j\omega\tau_d}$. τ_d is the delay associated with the optical fiber and can be controlled by varying fiber length. $\tilde{G}_{ampli}$ and $\tilde{S}$ are phasors that could be decomposed into phase and magnitude parts and represented as $G_{ampli}e^{j\phi_G}$ and $Se^{j\phi_S}$ and represent the RF amplifier gain and the photodetector responsivity respectively. ω_0 denotes the angular frequency of the optoelectronically generated RF signal.

B. Loop Delay

The delay associated to the fiber length τ_d, can further be expressed in terms of two distinct delays, τ_E and τ_{op} where τ_E and τ_{op} are induced by electrical and optical components respectively. The mode-spacing or the free spectral range (FSR) of the oscillator system is given by the formula:

$$FSR = \frac{1}{\tau_E + \tau_{op}} \quad (3)$$

The interdependence between FSR and the fiber length can be expressed numerically as follows if τ_{op} is defined in terms of c, the velocity of light, n_F, the optical fiber refractive index and L, the optical fiber length:

$$FSR = \frac{1}{\tau_E + \frac{n_F \cdot L}{c}} \quad (4)$$

From (4) it is evident that the FSR is inversely proportional to fiber length. For optical fiber lengths exceeding 1 km, the τ_E is negligible as compared to τ_{op} and hence the mode spacing can totally be controlled by varying the fiber length L.

C. Circuit Noise

The Relative Intensity Noise (RIN) of the VCSEL is the ratio between the mean square power fluctuation spectral density $< \Delta P^2 >$ and the square of average output optical power P_{avg}^2 and can be expressed as:

$$RIN_{VCSEL} = \frac{< \Delta P^2 >}{P_{avg}^2} \quad (5)$$

The Shot noise of the VCSEL can be represented as the mean square value of the shot noise current over a bandwidth Δf as $< i_{shot}^2 >$. Similarly, the noise due to thermal agitation of carriers in a semi-conductor for a bandwidth Δf can be expressed as the mean square value of the current fluctuations $< i_{th}^2 >$.

The total intrinsic noise spectral density of the oscillator system which is in fact a summation of effects from different noise sources can be mathematically described using the Leeson's model [2] as follows.

$$< i_{noise}^2 > = < i_{shot}^2 > + < i_{th}^2 > +$$
$$\left(RIN_{VCSEL} + RIN_{DRS} + RIN_{RRS} \right)$$
$$\cdot \Delta f \cdot I_{ph}^2 \quad (6)$$

RIN_{DRS} and RIN_{RRS} are two distinctly identifiable RINs due to inhomogeneities in the optical fiber where the subscripts DRS and RRS refer to double and reflected Rayleigh scatterings respectively. Duran et al. [3] have shown that the noisiest element in such an oscillator system is the optical fiber and it is in fact the perturbations related to DRS and RRS that affect the system performance and therefore the spectral purity of the optoelectronically generated oscillator signal. I_{ph} denotes the photodetector current.

The phase-noise power spectral density in terms of the total system noise power spectral density can be expressed as:

$$S_\Psi(f) = \left(1 + \frac{1}{f^2}\Big(\frac{f_{osc}}{2 \cdot Q_c}\Big) \right) \cdot$$
$$\frac{S_\Phi(f) \cdot G_{Ampli}^2}{P_{osc}}\Big(1 + \frac{f_c}{f} \Big) \quad (7)$$

Where f_{osc} is the oscillation frequency, Q_c, the quality factor of the delay line composed of all the loop elements and $S_\Phi(f)$ is the power spectral density of noise at the input of the amplifier.

IV. EXPERIMENT

Here, we present the experimental setup to obtain the desired oscillation frequency. A schematic diagram of the oscillator test-bench is presented in Fig.1. A 1.55 μm TO-46 packaged VCSEL is used as the principal optical source to generate the microwave signal. The output of the VCSEL is connected to a fiber-roll. The fiber-roll is connected to a

PIN photodetector with a nominal DC responsivity of 300 V/W. The output of the photodetector is fed to an RF filter centered at 2.49 GHz and connected to an RF amplifier. The bandwidth of the RF filter is 5 MHz. To determine the open-loop gain of the system, the output of the RF amplifier is connected to an ESA. The ESA has a resolution of 5 Hz. Once the unity gain open-loop condition is satisfied, a part of the RF amplifier output is used to modulate the VCSEL using a Y-coupler. The other branch of the Y-coupler is connected to the ESA to monitor and measure the opto-electronically generated microwave signal.

The VCSEL has threshold and rated currents of 1.58 mA and 12 mA respectively. The bias point was chosen to be at 6 mA so as to utilize the linearity of the device. The output optical power at 6 mA is 0.85 mW. The conversion efficiency of the VCSEL is 0.125 mW/mA. The RF amplifier connected to the RF filter has a gain of 35 dB. During the course of this experiment fiber-rolls of 100, 200, 300, 700 and 1000m lengths were used. All the fiber-rolls used were of Corning SMF-28 type. The output power of the oscillator signal varied from approximately 16 dBm to 20 dBm, depending on the length of the fiber-loop used to generate the signal. The output power, naturally, varies in inverse proportionality to the length of the fiber. The choice of fiber length was limited by VCSEL output optical power. For an optical fiber longer than 1000m , the attenuation of the optical signal becomes non-negligible and the oscillation conditions are not satisfied. Phase-noise curves at an offset of 1 kHz from the carrier to an offset of 100 kHz from the carrier have been plotted using the ESA. The 3-dB linewidth of the signal has also been measured using the ESA.

V. RESULTS

Fig.2 presents the phase-noise curves for different fiber lengths. A phase-noise of -107.57 dBc/Hz is found for a fiber length of 1000 meters, as is shown in the figure, at an offset of 10 kHz from the carrier. The phase-noise decreases with increase in fiber length. Fig.3 is the spectrum of the opto-electronically generated signal at 2.49 GHz. Fig.4 gives the linewidth of the oscillator signal measured using the ESA. A linewidth of 16 Hz is measured at a bias current of 6 mA using a 1000 meter long fiber. Table.I shows the lateral mode spacing variation as a function of fiber length. In conformance with the classical oscillator theory it can be seen that the FSR decreases with an increase in fiber length. It has already been demonstrated [4] that the spectral properties of the generated signal, such as the phase-noise, improve with the increase in fiber length since the $Q-$factor of this kind of oscillator and therefore the spectral properties are directly proportional to the loop delay. The utilization of different fiber lengths in fact proposes a trade-off between spectral purity of the signal and the spectral noise generated by unwanted lateral modes. Depending on the operating frequency range of the desired application a suitable optical fiber based delay line can be
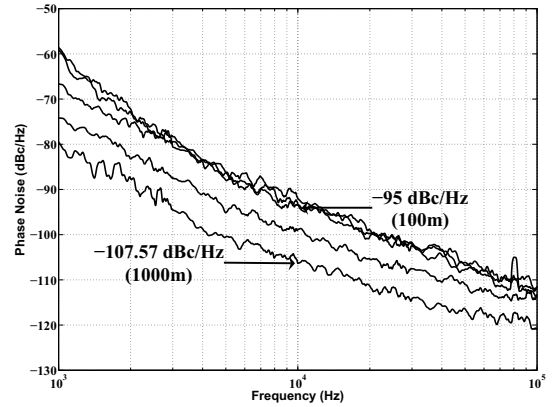

Fig. 2. Phase-Noise measurements for fiber lengths of 100, 200, 300, 700 and 1000 meters. The VCSEL bias current is kept constant at 6 mA.
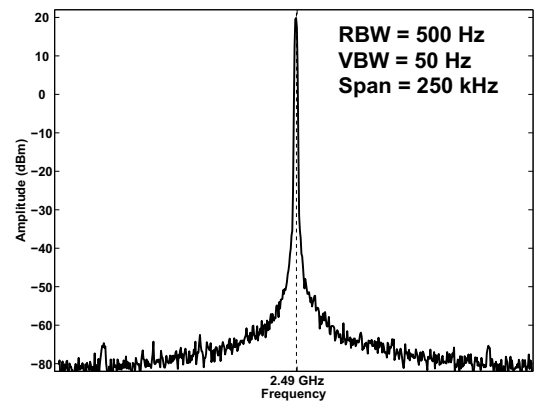

Fig. 3. Spectrum of the 2.49 GHz Oscillator Signal obtained using the 1.55μm single mode VCSEL.

selected for an optimal performance minimizing the phase noise. Fig.5 presents a signal generated using a 700m long optical fiber with two lateral modes.

VI. OEO COMPARISON

We have demonstrated a low phase-noise oscillator signal using a 1.55 μm single mode VCSEL. A comparison with other oscillators using the same technique but different optical sources is presented in Table.II. The parameter values for the multimode 850nm VCSEL and the DFB laser have been taken from Le Kernec et al. [4]. It is evident from the experiments performed that in order to achieve a similar performance, the electrical consumption of a DFB laser is more than 8 times that of a single-mode 1.55 μm VCSEL. The multimode 850 nm VCSEL consumes about twice as much as current than the 1.55 μm single mode VCSEL utilized in this experiment. In terms of parametric performance the VCSEL, which is an emerging technology, compares very well with the established DFB laser technology. The oscillator frequency is only limited by the availability of RF filter at a certain desired frequency and the intrinsic cut-off frequency of the optical
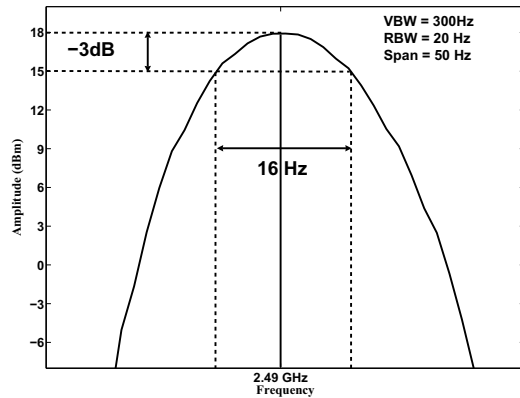
Fig. 4. Linewidth of the 2.49 GHz opto-electronically generated oscillator signal.
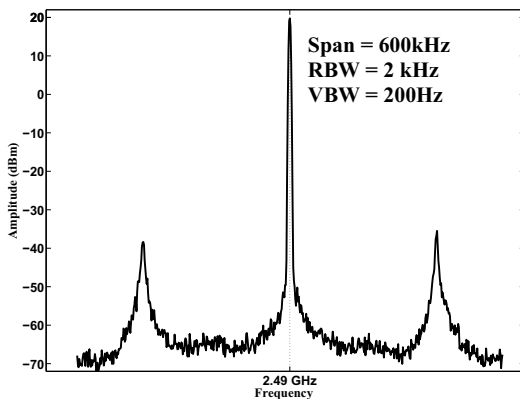

Fig. 5. 2.49 GHz Oscillator signal with lateral modes using a 700m long optical fiber. The VCSEL bias current is 6 mA.

source used. The VCSELs used in this experiment have an intrinsic cut-off frequency of 11 GHz. Given the availability of an RF filter, a sinusoidal signal of any frequency up to 11 GHz can be generated using the same optical source without compromising any of the advantages.

VII. CONCLUSION

The advantage of using 1.55 μm VCSELs to generate high spectral purity signals is their relative insensitivity to temperature fluctuations as compared to classical DFB lasers. Un-cooled, non temperature regulated VCSELs were used in this experiment to achieve results similar to those obtained by temperature-regulated DFB lasers. Eliminating the need to employ temperature-regulated components results in lighter and more compact systems, which is a primordial constraint imposed on embedded system applications. With the advances in VCSEL fabrication technology, high power 1.55 μm VCSELs have become available that can emit up to 4 mW at room temperature [5]. A longer optical fiber based delay-line can therefore be used to achieve

TABLE I
LATERAL MODE-SPACING VARIATION WITH INCREASE IN FIBER LENGTH

Sr. No.	Fiber Length (m)	FSR (kHz)
1.	100	1300
2.	200	790
3.	300	580
4.	700	210
5.	1000	180

TABLE II
A COMPARISON OF OPTO-ELECTRONIC OSCILLATOR CHARACTERISTICS USING DIFFERENT OPTICAL SOURCES

Parameter Sr. No.	DFB(SM) (1.55μm)	VCSEL(SM) (1.55μm)	VCSEL(MM) (850 nm)
Device Threshold Current (mA)	13	1.5	5
Operation Current (mA)	50	6	12.5
Phase-Noise @ 10 KHz (dBc/Hz)	-108	-95	-100
Oscillator Line-Width (Hz)	10	16	10
Fiber-Loop Length (m)	100	100	120
Oscillator Frequency (MHz)	900	2490	900
Temperature Regulation	Yes	No	No
Technique	Ring Oscillator	Ring Oscillator	Ring Oscillator

higher spectral purity. Furthermore the usage of single-mode VCSELs guarantees *a priori* a more spectrally pure system as compared to multimode VCSEL-based systems. The employment of single-mode 1.55 μm VCSELs combines the advantages of single-mode 1.55 μm DFB lasers and VCSELs while at the same time eliminating the inconveniences of high power consumption and temperature dependence.

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