Experimental Demonstration of an Ultra-Low Power Vertical-Cavity Surface-Emitting Laser for Optical Power Generation

S. Nazhan, Hassan K. Al-Musawi, Khalid A. Humood

Abstract**—**This paper reports on an experimental investigation into the influence of current modulation on the properties of a vertical-cavity surface-emitting laser (VCSEL) with a direct square wave modulation. The optical output power response, as a function of the pumping current, modulation frequency, and amplitude, is measured for an 850 nm VCSEL. We demonstrate that modulation frequency and amplitude play important roles in reducing the VCSEL's power consumption for optical generation. Indeed, even when the biasing current is below the static threshold, the VCSEL emits optical power under the square wave modulation. The power consumed by the device to generate light is significantly reduced to > 50%, which is below the threshold current, in response to both the modulation frequency and amplitude. An operating VCSEL device at low power is very desirable for less thermal effects, which are essential for a high-speed modulation bandwidth.

Keywords**—**VCSELs, optical power generation, power consumption, square wave modulation.

I. Introduction

AMONG wide light sources, VCSELs are strongly suggested to be a promising candidate for both fiber-optics and wireless communication systems, in terms of their cost efficiency, high speed (i.e., higher data transmission) and low power consumption [1], [2]. VCSELs are also considered to be ideal for gigabit Ethernet and optical interconnects [3], [4]. Recently, in [5] and [6], high-speed and energy-efficient 850 nm VCSELs with direct modulation operated error-free up to 57 Gbit/s.

The VCSELs' low power consumption minimizes the overall power dissipation of the optical sources, when it is used in high-speed data transmission systems. Conventional light sources, such as light-emitting diodes at a low-biasing current, experience an efficiency droop, which is a direct consequence of non-radiative recombination [7]. Both [8] and [9] have shown that lowering the drive current of optical sources can achieve lower power consumption, as well as higher modulation speed. Indeed, reducing the lasing current below the threshold is essential, in order to decrease the optical device's heat dissipation and increase its modulation bandwidth. Certainly VCSELs recorded very low threshold current of several micro ampere with high-efficient output power and performance [10], [11]. In laser diodes, the parameter that governs the minimum power consumption operates close to the threshold current, which is essential for the lasing operation. In [12], optical pumping has been used to reduce the lasing point by 50% of the threshold current, by means of optically pumping polarized electrons into the gain medium of a semiconductor laser. Reference [13] reports that enhancing coupling of spontaneous emission and reducing the optical loss can also lead to threshold lasing point drop in VCSELs. In previous years, a number of researchers have aimed to design efficient devices with high bandwidth, high slope efficiency, low lasing current, and low temperature sensitivity [14]. Current modulation (CM) is normally necessary when VCSEL is adopted for high-speed optical communications, which lead to a number of interesting, and complex dynamic behaviors in these devices, including chaotic, time-period pulsing dynamics [15]. The amplitude and frequency of CM promote rich, nonlinear behaviors, which affect the dynamics of the VCSEL. The nonlinearity depends on both the signal amplitude and the modulating frequency. The nonlinear behavior in semiconductor laser diodes could be attributed to the relatively small fraction of the spontaneous emission coupled into the lasing power [16]. A single transverse mode VCSEL dynamic, in addition to direct modulation current, was theoretically and experimentally investigated in [17] and [18], where increased the amplitude of the modulation current led to gain switching occurred in VCSELs' polarization modes, ultimately leading to lasing with a period of a doubling route to chaos.

This study investigates characteristics of the current injection versus optical lasing in an 850 nm VCSEL, by considering two important CM parameters: frequency and amplitude. The findings indicate that VCSEL starts lasing below the static threshold when square wave (SQW) modulation is adopted. Although the laser is biased below the threshold, the light is produced due to the modulation signal, which leads to drive the laser above threshold for part of the modulation cycle. As the modulation amplitude increases, so does the injection current, where the laser lases during part of the cycle reduce. Ultra-low power consumption for optical pulses, for leaser devices, is a subject of intense interest in the field of communication systems.

S. Nazhan is with Communication Engineering Department at University of Diyala, Baqubah, Diyala, Iraq (Corresponding author, phone: 00964-07735391157; e-mail: salam.n.a@uodiyala.edu.iq).

H. K. Al-Musawi is with the Electronic and Communication Department, University of Kufa, Najaf 54001, Iraq. (e-mail: hasank.baqir@uokufa.edu.iq).

Khalid A. Humood is with Department of Electronic Engineering, College of Engineering, University of Diyala, Iraq (e-mail: humoodkhalid@engineering.uodiyala.edu.iq).

II. Theoretical Analysis

The effect of the spontaneous emission, coupled into the lasing mode, can be examined using rate equations, which define the irregular dynamics behaviors of directly modulated semiconductor lasers.

$$\frac{dN}{dt} = \frac{I_{dc}+I_m \sin(\omega t)}{qV} - \frac{N}{\tau} - g(N - N_o)\frac{S}{1+\epsilon S}, \quad (1)$$

$$\frac{dS}{dt} = \Gamma g(N - N_o)\frac{S}{1+\epsilon S} - \frac{S}{\tau_p} + \Gamma\beta C_1 N^2, \quad (2)$$

where N and S are the injected carrier density and the photon density inside the cavity, I_{dc} is the dc bias current, I_m is the modulation current, $\omega = 2\pi f$, f is the modulation frequency, q is electron charge, V is the active volume, τ is the carrier lifetime, g is the gain coefficient, N_o is the carrier density at transparency, Γ is the optical confinement factor, β is the spontaneous emission factor, C1 is the recombination coefficient, τ_p is the photon lifetime, and ϵ is the nonlinear gain compression factor.

The expression for optical power above the threshold current (I_{th}) is given by [19]:

$$P_o = \eta_s(I - I_{th}) = \eta_d \frac{h\nu}{q}(I - I_{th}) = \eta_i \frac{a_m}{a_i + a_m}\frac{h\nu}{q}(I - I_{th}), \quad (3)$$

where I is the operation current, η_s is the slope efficiency, η_d is the differential quantum efficiency, $h\nu$ is the photon energy, η_i is the internal efficiency, a_i is the photon losses, and a_m is the mirror loss parameter. Output power is directly proportional to I_{th}, which increases as I_{th} decreases. The power conversion efficiency is $\eta_p = (\frac{P_o}{V_p I})$, where V_p is the bias voltage. For the case of the above, I_{th}, η_p can be written as [3]:

$$\eta_p = \eta_d \frac{E_g}{V_p}\left(1 - \frac{I_{th}}{I}\right) \cong \eta_d \quad (4)$$

Since I_{th} is somewhat small for VCSEL devices, η_p is expected to be relatively high.

The total injection current I(t) is defined as [20]:

$$I(t) = I_{th} + I_{dc}[1 + M \sin(\omega t)], \quad (5)$$

where M is the electrical modulation index. The optical output power P can be measured from fundamental and other harmonic response and it can be written as [21]:

$$P(t) = P_o + P_1.\sin(\omega t) + P_2.\sin(2\omega t), \quad (6)$$

High nonlinearity in the output power of VCSEL devices has been reported in situations in which the laser is biased near the threshold current at a higher modulating frequency [16], which thus leads to harmonic distortions.

III. Experimental Setup Details and Results View Stage

This experiment uses a commercial 850 nm VCSEL, which, over a range of bias current, has linear output power. The VCSEL is driven by a Newport 505B laser driver in addition to a thermoelectric temperature controller (TED 200C) to within 0.01 °C. The VCSEL is subjected to CM using an external signal generator (Tektronix, 2 GS/s, 240 MHz). The laser output beam is first collimated using an objective lens, prior to being detected by an identical optical receiver. The VCSEL optical output power is measured using an optical power meter (Anritsu, ML9001A). The output optical power is captured and stored in a digital oscilloscope (Agilent, 6 GHz) for further analysis. The standalone VCSEL lases in the fundamental mode over the entire bias current range (0–9 mA).

The device characteristic with CM was investigated for a range of modulation frequencies of 100 Hz to 100 MHz, and modulation amplitudes of 50 mV, 250 mV, and 450 mV. The power response of the total current of the free running VCSEL (i.e., no modulating signal) is shown in Fig. 1, which illustrates that the VCSEL started lasing at I_{th} of ~1.6 mA.

Next, we will describe the dynamics of VCSEL showing the effects of CM by using both frequency and amplitude. The performances of VCSEL when driven with a SQW are evaluated in the next section in terms of output power as a function of driving current focusing on lasing before I_{th}.

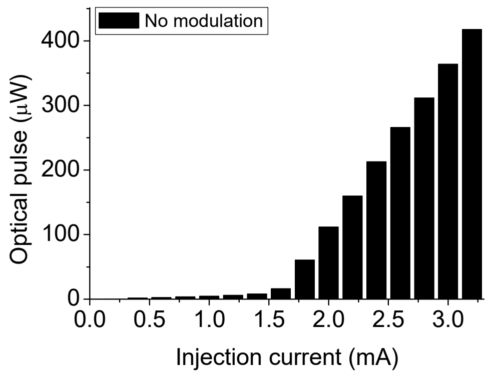
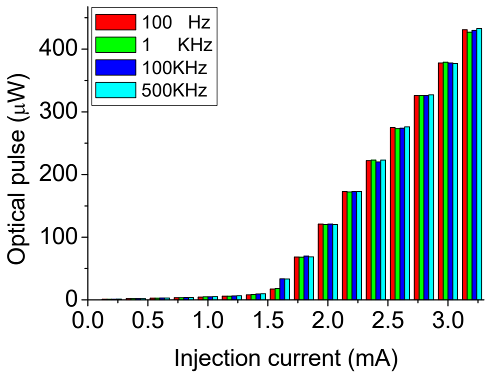


Fig. 1 The output optical power as a function of bias current of standalone VCSEL with no modulation signal

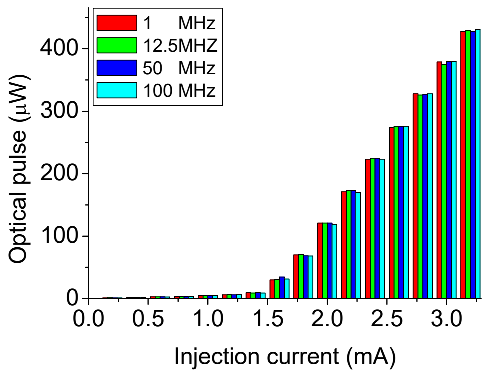
A. Modulation Parameters' Effect

The optical pulses response versus the injection current are presented in Fig. 2, where VCSEL is modulated with SQW signal using a range of frequencies of 100 Hz, 1 KHz, 100 KHz, 500 KHz (Fig. 2 (a)) and 1 MHz, 12.5 MHz, 50 MHz and 100 MHz (Fig. 2 (b)) with fixed modulation amplitude at 50 mV. The modulation frequency is smaller than the relaxation oscillation frequency of the VCSEL. Note that the frequency range shown in Fig. 2 is applied to all measurements but under different modulation amplitude values. The maximum rating bias current was set at 3.25 mA and the range of the frequencies is separated in two figures for clarity. For the range of frequencies between 100 Hz to 500

KHz, there is no significant change in the optical power value observed compared to the standalone VCSEL (i.e. without modulation) output power. The optical powers at low frequencies of 100 Hz to 1 KHz, which before threshold current, display low output optical power values. However, for the frequencies range of 1 MHz to 100 MHz, the power for the optical lasing progressively increases over the entire range of the bias current where the VCSEL emits before the static threshold point with low optical power reaching to about 30 micro Watt at ~1.5 mA.



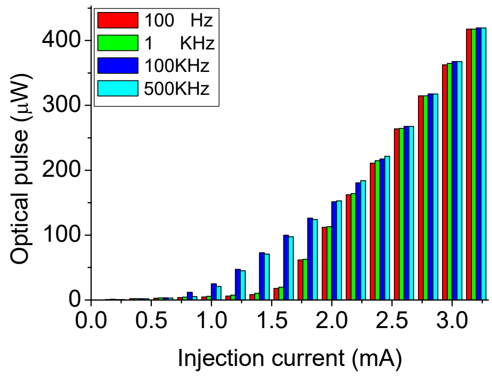
(a)



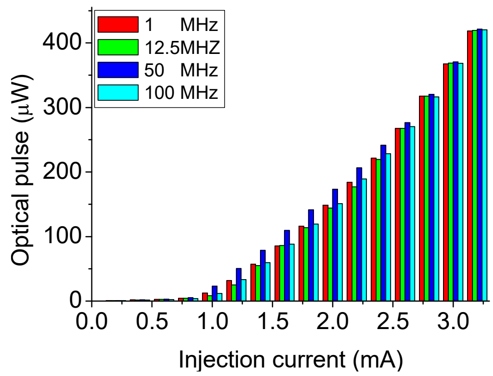
(b)

Fig. 2 Measured total optical power of the VCSEL versus the bias current with SQW modulation and fixed amplitude of 50 mV for a range of frequencies of (a) 100 Hz, 1 KHz, 100 KHz, and 500 KHz, (b) 1 MHz, 12.5 MHz, 50 MHz, and 100 MHz

At low value of modulation amplitude of 50 mV, the optical power level is almost the same for all frequencies at each point of the injection current range. However, as the amplitude increases to 250 mV, the device starts lighting at ~1 mA of the injection current, which indicates that the injection current for lasing is reduced from 1.6 mA to ~1 mA, with modulation frequency of 100 KHz and 500 KHz, as shown in Fig. 3 (a). Further increases of modulation frequency (i.e. 1 MHz to 100 MHz) lead to decrease the laser output point before static threshold current from ~1.6 mA to ~0.5 mA as illustrated in Fig. 3 (b). The output power for modulation frequency of 50 MHz is a little high compared with the others, particularly at low injection current as we can see in Fig. 3 (b). The optical power value is about 80 micro Watt at 1.5 mA under modulation frequency of 50 MHz. The efficiency of the laser emitting does also depend on the modulating frequency, as display in Fig. 3 (a), where its decreases around threshold point depending on both modulation frequency and amplitude.



(a)

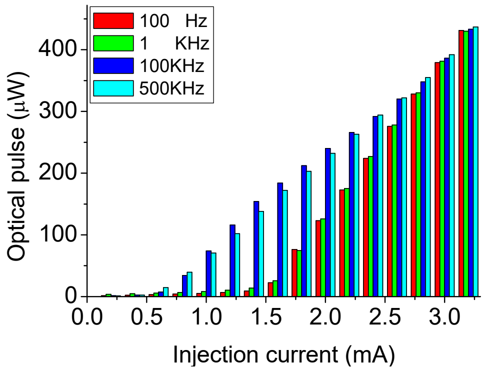


(b)

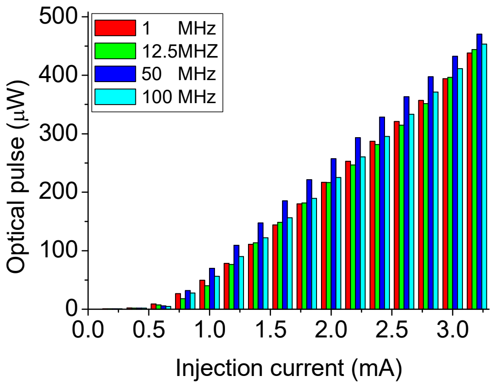
Fig. 3 Measured total optical power of the VCSEL versus the bias current with SQW modulation and fixed amplitude of 250 mV for a range of frequencies of (a) 100 Hz, 1 KHz, 100 KHz, and 500 KHz, (b) 1 MHz, 12.5 MHz, 50 MHz, and 100 MHz

From a physics point of view, at low bias levels, the excited carriers fail to duplicate the entire injected signal photons, thus resulting in majority of the received photons remaining in the cavity region and not being amplified. As a consequence, the output power response is summation of duplicated stimulation emission power and the external injection power with the latter being the dominant [15]. Fig. 4 shows the total output optical power of the VCSEL as a function of the injection current with SQW modulation and fixed amplitude at 450 mV for the same range of frequencies shown in Fig. 3. The output power obviously increases when applied 450 mV modulation amplitude depending on modulation frequency value.

In Fig. 4 (a), the optical power values at frequencies of 100 KHz and 500 KHz is dominant over the other frequencies. By contrast, the power consumption for lasing at 450 mV is less than this of the power at 50 mV and 250 mV as discussed before, where the power change follows the amplitude value. Besides, the results show that modulation parameter can be reduced the power consumption for more than 50% for the optical power generation by VCSEL. This can be attributed to the total injection current of VCSEL, where it becomes the sum of the bias current and the modulation current, which results in increased stimulation emission and yields to increase the photon density then the output power of the laser.



(a)



(b)

Fig. 4 Measured total output optical power of the VCSEL versus the bias current with SQW modulation and fixed amplitude of 450 mV for a range of frequencies of (a) 100 Hz, 1 KHz, 100 KHz, and 500 KHz, (b) 1 MHz,12.5 MHz, 50 MHz, and 100 MHz.

The relationship between the lasing point of VCSEL at the bias current and modulation frequency (in log scale) depending on a range of amplitude values is depicted in Fig. 5. At low frequency range between 1 Hz to 1 KHz, optical power of VCSEL is around the threshold current between 1.4 mA and 1.6 mA. The bias current values required for lasing are significantly reduced to ~0.8 mA and ~0.2 mA at signal amplitudes of 250 mV and 450 mV, respectively for higher frequencies range from about 50 KHz to 100 MHz. Hence, frequency modulation contributes to important reduction particularly at modulation amplitude of 250 mV and 450 mV. The threshold current reduction based on modulation parameters in VCSEL is found in literature, where pulse packages and reduction of threshold current are demonstrated theoretically in [22] which support our finding.

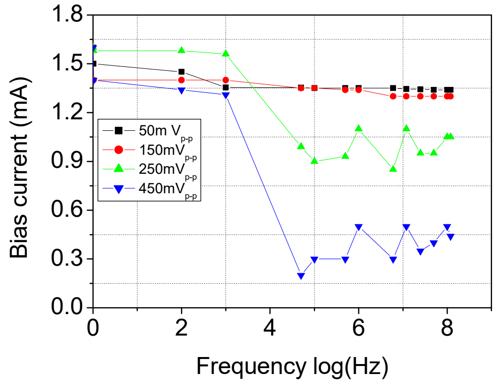


Fig. 5 The bias current against the frequency (scale in log (Hz)) for four values of modulation amplitude of 50 mV, 150 mV, 250 mV, 450 mV

Based on the above experiment results, it can be seen that the response of the threshold current with respect to the modulation frequency follows that of a low-pass filter together with a dc component. More specifically, it can be written as:

$$I_{\text{tm}}(\omega) = \frac{K\omega_c}{\sqrt{\omega^2+\omega^2{}_c}} + I_o, \tag{7}$$

where ω is the frequency in rads^{-1}, K is a positive constant depending on the amplitude of modulation, ω_c is the cut off frequency and I_o is the dc component.

IV. Conclusion

An experimental investigation of VCSEL characterizations under modulation signal using modulation parameters of amplitude and frequency is presented. The effects of both frequency and amplitude on the power required for lasing in VCSEL were investigated. Wide range of frequency, i.e. 100 Hz to 100 MHz depended on different values of amplitude of 50 mV; 150 mV; 250 mV; and 450 mV were applied. The results showed that lasing of the VCSEL is highly dependent on both frequency and amplitude of modulation signal. Furthermore, it is demonstrated that the applied modulation parameter led to reduce the power consumption. VCSEL was start lasing before static threshold current, where it was obviously appeared at 250 mV and 450 mV of modulated amplitude over a wide range of modulation frequency. Power consumption for the laser lasing was reduced by more than 50%. The slop efficiency decreased with increasing amplitude of the input signal close to threshold current value of VCSEL.

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S. Nazhan is born in Baqubah/Iraq in 1971. He received the BS and MS degrees in physics, and electronics physics from Al Mustansiriya University, Baghdad, Iraq, in 1998 and 2005 respectively, and he received the PhD degree in optoelectronics from Northumbria University, Newcastle, United Kingdom in 2016. He joined the Optoelectronics Research Group as a PhD researcher at Bangor University, Wales, UK in 2011- 2012 and Optical Communications Research Group at Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne, UK until May 2016.

His research focuses on optical and electrical characteristic of vertical-cavity surface emitting laser for free space optical communications. He already published around 21 research papers in top journals in the field, and publish one patent.

Dr. Nazhan becomes a Member (M) of IEEE in 2013 and he is a technical committee member at several international conference and journals. He serves as a review board member for a number of international journals. He also presented his research in a number of conferences and events. Finally, his current research interests include polarization properties, optical chaotic signal, and nonlinearity behaviors of VCSEL. Furthermore, Dr. Nazhan is currently Lecturer and the principal investigator of number of undergraduate students at communication engineering department at University of Diyala, Iraq.

Dr. Hassan K. Al-Musawi received the Bachelor’s degree in Electrical and Electronic Engineering from the University of Technology in Baghdad, Iraq in 1998, starting career as consultant engineer in the University of Kufa, Iraq for the Electrical projects development. He received the MSc degree with distinction in Optoelectronic and Communication Engineering from Northumbria University at Newcastle, UK in 2010, then he worked as assistant lecturer in the Faculty of Engineering, University of Kufa, Najaf, Iraq. He received the PhD degree on the Radio-over-Fibre (RoF) and Radio-over-Free Space Optics (RoFSO) for the indoor and outdoor communication systems in Optical Communication Research Group at Northumbria University, UK in 2017. He is currently working as a lecturer at the Department of Electronics and Communications, University of Kufa.

Hassan K. Al-Musawi becomes a Member (M) of IEEE in 2014 and he is a technical committee member at several international conferences and journals. He serves as a review board member for a number of international journals and conferences. He also presented his research in a number of conferences and events. Finally, his research interests include the area of indoor and outdoor radio-over-fibre (RoF) system integration and FSO applications. In addition to the mobile communication systems including fifth-generation (5G) technology.

Assist Prof. Khalid A. Humood received his bachelor's degree in electronic and communication engineering from Mosul University in 1979. He received a higher diplom degree in electrical engineering / electronic engineering from the University of Technology in 1982 and obtained a master's degree in electrical engineering / electronic engineering from the University of Technology In 1991 and received a Ph. D degree in electrical engineering / electronic engineering from the University of Technology in 2007. He worked as a lecturer at the Rashid College / Technological University for the period 1993-2007. Worked as a lecturer at the Faculty of Engineering / University of Diyala since 2007-. The field of research interest in the analysis and design of systems in the field of electronics engineering and communications. He has more than one scientific research published in local and international magazines