Cryogenic Oxide-VCSEL at 2.8 K Demonstrates Record Bandwidth f_{-3dB} > 50 GHz, P_{out} > 14 mW and PAM-4 Data Rate up to 128 Gb/s

Haonan Wu, Wenning Fu, Zetai Liu, Yulin He and Milton Feng
Department of Electrical and Computer Engineering & Holonyak Micro and Nanotechnology Laboratory,
University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA. Author email address: mfeng@illinois.edu

Abstract: We report record speed-power and ultrahigh linearity performance for a 6.8 um oxide-aperture VCSEL operated at 2.8K. The device demonstrates data rate up to 128 Gb/s PAM-4 and 64 Gb/s NRZ.

1. Introduction

Recent technical advancements in cryogenic computing, such as single-flux-quantum (SFQ) superconducting computing and quantum computing, have paved the way for next-generation ultrafast processors [1], [2]. However, there's a significant challenge: SFQ superconducting circuits must operate at liquid helium temperature, making the reliable high-speed data communication to room temperature (RT) challenging. Similarly, the Cryo-CMOS SoC qubit controller, which is essential for achieving scalability in quantum computing, has been demonstrated at 4 K and necessitates digital interfaces to room temperature [3]. As a result, there's a growing need for an interconnect solution that's both energy-efficient and capable of high-speed data transfer between 4 K and room-temperature (RT) electronics. Compared to electrical links from RT to 4 K, optical fiber interconnects exhibit marked advantages, notably reduced frequency-dependent signal attenuation and negligible thermal leakage. Therefore, the CryoVCSEL has been posited as a key transmitter of the cryogenic optical link, primarily due to its high bandwidth @ low bias current for energy-effcient high speed data communication. [4], [5].

By 2012, advancements in Cryogenic oxide-confined VCSELs (Cryo-VCSELs) for cryogenic applications achieved threshold current of ~0.5 mA at 88 K and 10 Gb/s NRZ eyes at 145 K [6], [7]. In 2021, the UIUC team showcased Cryo-VCSELs bandwidth exceeding 50 GHz at 82 K [8], [9]. Subsequent to this breakthrough, the team engineered packaged fiber-coupled Cryo-VCSEL lase at 2.6 K with I_{th} = 0.177 mA [10] and 100 Gbps PAM-4 [11], [12]. Later in 2022, the UIUC team demonstrated Cryo-VCSEL based optical datalink with superconducting SFQ circuits driver to demonstrate up to 20 Gb/s NRZ error-freeBER test via OM4 fiber to the RT optical receiver [13].

In this work, we report the first below-liquid-helium-temperature on-wafer probing measurement of semiconductor laser. The 6.8 um oxide-aperture Cryo-VCSEL demonstrates record 14.1 mW emission power at I/I_{th} ~ 200, and the small-signal bandwidth at 2.8 K exceeds 50 GHz. Furthermore, with high-speed performance optimized cryogenic RF path, the eye-diagrams of 64 Gbps NRZ and up to 128 Gbps PAM-4 data transmission from Keysight M8194A to oxide VCSEL at 2.8 K, and to photoreceiver at room temperature is demonstrated. The Cryo-VCSEL data link passes the transmitter qualification for 400/800GBASE-DR optical link specified in IEEE 802.3df [14], [15].

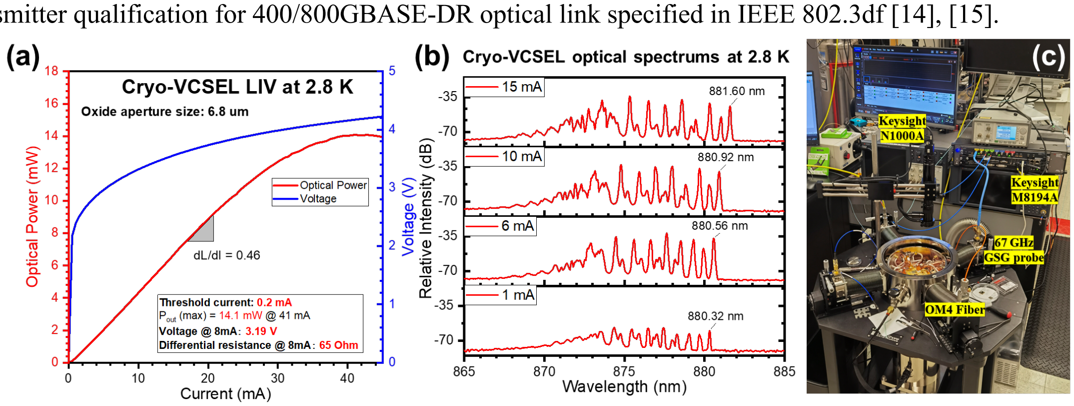

Fig. 1. (a) LIV curve of the 6.8 um aperture Cryo-VCSEL measured at 2.8 K. The threshold current is 0.19 mA and the emission wavelength is ~ 880.32 nm at I_{bias} = 1mA. The optical power is measured using NIST calibrated large-area photodetector. (b) The laser spectrum of the Cryo-VCSEL measured at 2.8 K using Advantest Q8384 optical spectrum analyzer. (c) A photo of the measurement setup, including Lakeshore cryostat, Keysight M8194A Arbitary waveform generator and N1000A sampling scope.

The Cryo-VCSEL LIV (light, voltage vs. current) curve up to 45 mA bias current and optical spectrum from 1 mA to 15 mA are shown in Fig 1 (a) - (b). The LIV measurement uses Thorlabs FDS1010-CAL, a NIST calibrated large-area photodetector, to receive the optical power from Cryo-VCSEL; whereas the optical spectrum measurement uses

OM4 lens fiber to couple the light into Advantest Q8384 optical spectrum analyzer. The Cryo-VCSEL threshold current is down to 0.2 mA at 2.8 K, and the L-I curve shows supreme linearity up to 25 mA bias current. In other words, the L-I curve slope efficiency remains constant until the $I/I_{th} > 125$. Moreover, the 6 um aperture Cryo-VCSEL does not exhibit thermal-rollover until $I_{bias} > 40$ mA (I/I_{th} exceeds 200), and the maximum optical power output reaches 14.1 mW. For the optical spectrum, the fundamental mode shifts from 880.32 nm at $I_{bias} = 1$ mA to 880.56 nm at $I_{bias} = 6$ mA, and to 881.6 nm at $I_{bias} = 15$ mA. Despite the increasing laser output power, the location and number of optical modes remains nearly constant due to superior thermal performance of Cryo-VCSEL. Furthermore, the Cryo-VCSEL exhibits no degradation in laser threshold and output power in performance after more than thirty thermal cycles from 300 K to 2.8 K, and stress test with I_{bias} up to 50 mA.

2. On-wafer probing small-signal bandwidth characterization of Cryo-VCSEL at 2.8 K

After the DC characterization of Cryo-VCSEL, the small-signal optical response of Cryo-VCSEL at 2.8 K is measured via on-wafer probing and standard Short-load-open-thru (SLOT) calibration, as shown in Fig 2. The bias dependent RF return loss of 2.8 K Cryo-VCSEL up to 50 GHz combining with physical-based model fitting [16] is shown in Fig. 2 (a), whereas the Fig. 2 (b) demonstrates the measured optical frequency response of 2.8 K Cryo-VCSEL. When $I_{bias} = 1$ mA, the differential resistance is around 260 Ohms, far above 50 Ohm measurement RF path, resulting in significant impedance mismatch. As the bias current increases, the return loss (S_{11}) gradually shifts inwards into the center of the smith chart. Furthermore, as the bias current increases, the resonance frequency f_R drastically increases with the increasing stimulated rate and photon density. At high bias currents above 7 mA, the frequency response curve is overdamped by the reduced carrier recombination lifetime to have a flat optical response with 3dB bandwidth exceeding 50 GHz.

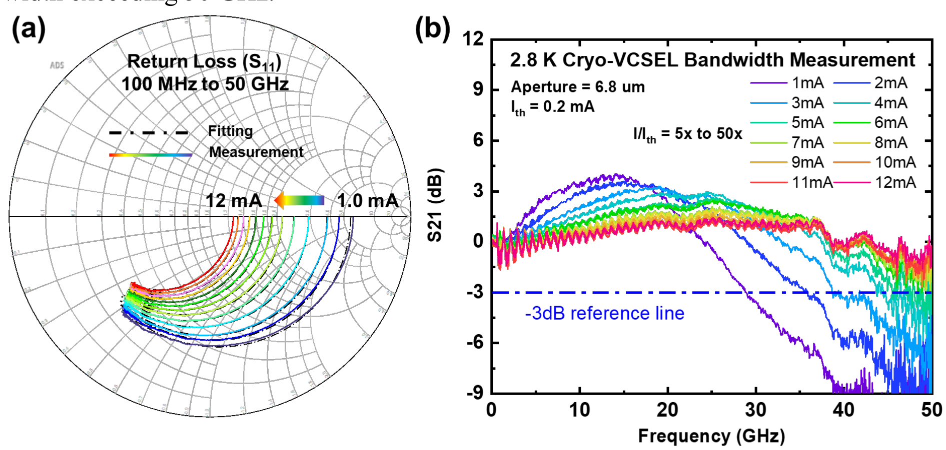

Fig. 2. (a) Typical measured and fitted RF return loss (S_{11}) of 2.9 K Cryo-VCSEL up to 50 GHz. (b) Typical measured extrinsic optical frequency response of 2.8 K Cryo-VCSEL with varying bias current from 1 mA up to 12 mA. The 3dB bandwidth of the Cryo-VCSEL exceeds 50 GHz as $I_{bias} > 7$ mA.

3. Directly modulated Cryo-VCSEL at 2.8 K for up to 128 Gb/s PAM-4 and 64 Gb/s NRZ Optical Link

Finally, the high-speed data-transmission capability of the fiber-coupled 2.8 K Cryo-VCSEL is characterized up to 128 Gbps. The Keysight M8194A arbitrary-waveform-generator (AWG) generates up to 128 Gbps pseudo-random binary sequence (PRBS-13) to directly modulate the Cryo-VCSEL operating at 2.8 K. The output optical signal transmits through the integrated OM4 fiber and directly coupled into the Thorlabs RXM25BF InGaAs photoreceiver at RT via vacuum fiber feedthrough. In addition, the in-system calibration in M8194A is performed to partially offset the frequency-dependent RF attenuation in the path. The Keysight 86118A 70 GHz sampling head and 86107A precision timebase module installed on the N1000A are used to capture and analyze the eye diagrams. No Forward-error-correction (FEC) is used in this work, and all measured eye diagrams are un-averaged. All measured eye-diagrams pass standard 4-tap Feed-Forward-Equalizer (FFE) for transmitter dispersion eye closure (TDECQ) qualification testing. The 64 Gbps PAM-4 and NRZ eye diagram of 2.8 K Cryo-VCSEL optical data link are shown in Fig 4 (a)-(b). The measured TDECQ for PAM-4 eye diagram is 0.40 dB, and the TDEC value for 64 Gbps NRZ is 3.17 dB, respectively. In Fig 3 (c), it is shown that the Cryo-VCSEL optical link easily passes the 400/800GBASE transmitter qualification test with TDECQ = 2.56 dB, as specified in the latest IEEE 802.3d standard [14], [15]. In addition, the Cryo-VCSEL optical link eye diagram remains clear open as the data rate ramps up to 128 Gbps, as shown in figure 4 (d). It is clear that the major limitation of the Cryo-VCSEL optical data link is the receiver side given that the photodetector bandwidth is up to 25 GHz [12].

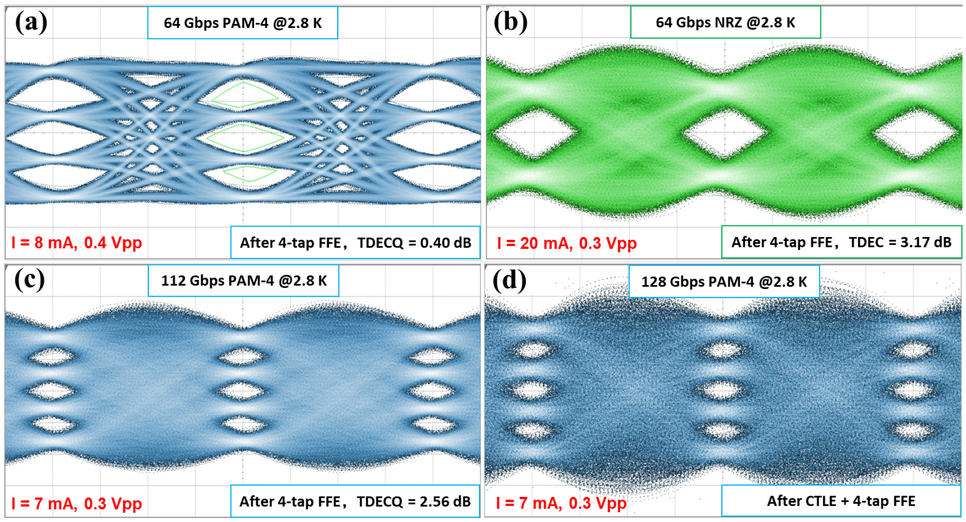

Fig. 3. (a-d) 2.8 K Cryo-VCSEL Driven by Keysight M8194A: PAM-4 and NRZ Optical Eye Diagrams up to 128 Gbps. The driving RF signal amplitude and Cryo-VCSEL bias current are labeled in the lower left corner. All measured eye-diagrams pass the a standard 4-tap Feed-Forward-Equalizer (FFE) for TDECQ qualification testing.

4. Summery

In this work, the Cryo-VCSEL at 2.8 K is characterized using on-wafer probing technique to demonstrate eye open up to 128 Gb/s PAM-4 and TDECQ = 2.56 dB at 112 Gbps. Given that demonstration of higher data rate is limited by the 25 GHz photodetector, and the fabricated oxide-VCSEL has measured > 50 GHz modulation bandwidth for low bias current (~7 mA), it is possible to 112 Gb/s NRZ and 224 Gb/s PAM-4 data transmission with sub-100 fJ/bit operation at 4K in the future work.

Acknowledgement: This work was supported by Dr. William Harrod (IARPA) on Develop Ultralow Power Cryo-VCSELs for 4K Fiber Data Link under ARO Grant No. W911NF-22-1-0229. The high-speed VCSEL PAM-4 test is partially supported by Dr. Mike Gerhold for the Army Research Office (ARO) grant to UIUC under No. W911NF-21-1-0022.

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