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Jukka Viheriälä, Topi Uusitalo, Heikki Virtanen, Behzad Namvar, Patrik Rajala, Sanna Ranta, Teemu Hakkarainen, Antti Tukiainen, Guilhem Almuneau, Mircea Guina

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Development of VCSELs for cryogenic (4.2 K) optical interfaces

Jukka Viheriälä
Engineering and Natural
Sciences
Tampere University
Tampere, Finland
Jukka.Viheriala@tuni.fi

Topi Uusitalo
Engineering and Natural
Sciences
Tampere University
Tampere, Finland
Topi.Uusitalo@tuni.fi

Heikki Virtanen
Engineering and Natural
Sciences
Tampere University
Tampere, Finland
Heikki.Virtanen@tuni.fi@tuni.fi

Behzad Namvar
Engineering and Natural
Sciences
Tampere University
Tampere, Finland
Behzad.Namvar@tuni.fi

Patrik Rajala
Engineering and Natural
Sciences
Tampere University
Tampere, Finland
Patrik.Rajala@tuni.fi

Sanna Ranta
Engineering and Natural
Sciences
Tampere University
Tampere, Finland
Sanna.Ranta@tuni.fi

Teemu Hakkarainen
Engineering and Natural
Sciences
Tampere University
Tampere, Finland
Teemu.Hakkarainen@tuni.fi

Antti Tukiainen
Engineering and Natural
Sciences
Tampere University
Tampere, Finland
Antti.Tukiainen@tuni.fi

Guilhem Almuneau
LAAS-CNRS, Université de
Toulouse, CNRS, 7 Avenue du
Colonel Roche, 31400 Toulouse,
France
Guilhem.Almuneau@laas.fr

Mircea Guina
Engineering and Natural
Sciences
Tampere University
Tampere, Finland
Mircea.Guina@tuni.fi

Abstract— *Vertical cavity surface emitting lasers operating at 4.2K are developed for energy efficient optical links between cryogenic systems and room-temperature data storage systems. Design considerations, material models, and validation of required electro-optical-thermal models are presented. Successful operation at mA-level injection is demonstrated.*

Keywords—VCSEL, LD, Laser, cryogenic

I. INTRODUCTION

Quantum computing has captured a tremendous level of interest owing to its predicted computational power that can solve problems that cannot be tackled efficiently using classical supercomputer schemes [1]. To maintain quantum coherence, majority of quantum computing systems involve operation at *cryogenic* temperature. While quantum processing with a limited number of qubits has been demonstrated in many types of systems, scaling of the number of qubits to achieve computation supremacy has to overcome limitations related to interfacing with room temperature systems [2]. In other words, the increasing number of electrical wirings not only introduces bandwidth limit but also more heat into cryostat, requiring larger and more complex cryostat to preserve the quantum features. Expectation is that optical fiber connections could provide more scalable solution as data bandwidth in a fiber can be very high and as silica fibers offer relatively high thermal insulation [3].

At room temperature, short haul optical transceivers [4] utilize often vertical cavity surface emitting lasers (VCSELs).

Besides offering immense affordability, VCSELs allow relatively high data bandwidths, very compact size, and low power consumption. Such performance-KPIs are topical also for cryogenic photonics towards quantum computing. Although there are some very early demonstrations from cryogenically operated VCSELs ([5], down to 77 K and [6] down to 6 K) only very recently high-performance lasers with power consumption below 100 fJ/bit have become available [7].

This work focuses on analyzing VCSEL operation at 300 K to 4.2 K temperature range by exploring physical models behind VCSEL operation. Focus is towards understanding microcavity – gain resonance condition and its temperature dependency, to develop working electrical models under conditions where thermionic emission is limited and to understand internal thermal profiles in VCSEL during its low (ambient) temperature operation. We present performance merits for fabricated devices and analyze main limiting factors towards low energy per bit operation.

II. DEVICE STRUCTURE AND FABRICATION

Top emitting VCSEL device structure included, on n-substrate, 36-period high reflective Bragg mirror (DBR) formed with n-Al_{0.12}GaAs high-index and n-Al_{0.9}GaAs low-index layers. Top-DBR was formed with 26 pairs of p-Al_{0.12}GaAs high-index and p-Al_{0.9}GaAs low-index layers. Top DBR stack also included 15 nm thick p-Al_{0.98}GaAs layer for thermal wet oxidation. Microcavity was formed between top and bottom DBRs from NiD-Al_{0.25}GaAs and contained three 5-nm-thick In_{0.12}GaAs Quantum Wells (QWs). Topmost layer on the p-side

was p-GaAs for electrical contact. This device structure was grown with solid source molecular beam epitaxy.

Top emitting wet oxidized device structure was formed by fast three lithography step process designed to provide fast feedback between design rounds. First lithography step was towards making different size of mesa structures that were dry etched and subsequently wet oxidized. Furthermore, p-epi-side of the wafer was insulated and planarized with SiO₂ and BCB-layers. These layers were patterned towards removing insulation from top of the mesa after which p-metal was deposited to form p-contact and p-contact pad. Substrate was thinned down to 100 μm and backside was metallized with AuGeNi/Au and thermal annealed.

III. MICROCAVITY DESIGN AND VALIDATION

Microcavity design aims to achieve proper detuning between QWs emission and the microcavity to enable low threshold operation. Photoluminescence measurements on QW indicate that the rate of changing emission-wavelength with temperature was reduced at average 0.13 nm / K when temperature was dropped from room temperature to 4.2 K. Furthermore, we developed reflectance measurement system that was able to extract microcavity resonance vs wavelength from reflectance. As shown in figure 1, this system allowed measurements characterizing non-linear reduction of resonance wavelength at low temperatures. Measurements were fitted to reflectance index model for low and high index DBR-layers. Results indicated that refractive index contrast is maintained over whole temperature range, indicating that mirrors reflectance are not significantly changed over the operational temperature range. However, extracted index values differed from the model predicted values at temperatures below 100 K.

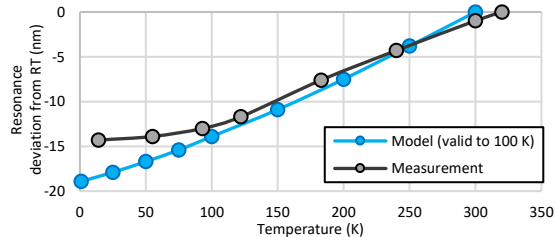
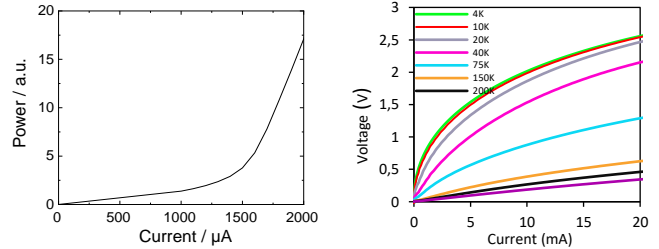


Fig. 1. Modelled microcavity resonance wavelength vs measured.

IV. DEVICE PERFORMANCE

Devices were packaged on TO-can that was possible to add into cryostat equipped with optical window allowing collection of light at room temperature side of the window. DC cabling was wired to PCB holding TO-can. Such set-up allowed device characterization at cryostat minimum temperature around 4 K and during the ramp between low and high temperature. Devices with (300 μm²) circular oxide aperture were measured to achieve 1.5 mA threshold (see figure 2) around 4.2 K indicating threshold current density of 500 A/cm². Spectral measurements at 30 K showed cavity-gain detuning of -6 nm at operation wavelength around 860 nm. In comparison to reference devices designed for room temperature operation, we estimated that low temperature operation allows 5 times lower threshold current density due to effects such as better carrier

confinement and increased thermionic emission lifetime. Devices showed strong voltage increase compared to room temperature operation (as shown in figure 2). This is partially due to many heterointerfaces in DBR-structure causing voltage increase to build up over device structure. Presentation elaborates directions towards better electrical design.



Left: Current-Output power curve around 4.2 K. Right: p-DBR mirror I-V curve as a function of temperature.

CONCLUSIONS

Results show that properly optimized VCSEL can be in many ways ideal source for short haul data-transfer from a system operating at cryo-conditions to receiver either in cold or at room temperature. At cryo-conditions these micro-cavity devices show significantly reduced lasing threshold current indicating potentially very low power consumption. However, VCSEL devices require careful heterointerfaces design taking in considerations arising relatively low thermionic emission at 4.2 K.

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