Electrically-Pumped 1050-nm MEMs Tunable VCSELs Wide tuning Range for OCT Applications

Dalila Ellafi
Bandwidth10 LTD.
Berkeley, CA, USA
dellafi@bandwidth10.com

Michael Yang
Bandwidth10 LTD.
Zhongli, Taiwan
michael@bandwidth10.com

Sam Kim
Bandwidth10 LTD.
Berkeley, CA, USA
skim@bandwidth10.com

Neelanjan Bandyopadhyay
Bandwidth10 LTD.
Berkeley, CA, USA
nbandyopadhyay @bandwidth10.com

Chris Chase
Bandwidth10 LTD.
Berkeley, CA, USA
cchase@bandwidth10.com

***Abstract*—We report an electrically-pumped 1050 nm micro-electro-mechanically-tunable vertical-cavity surface-emitting-laser (MEMS-VCSEL) with a record single-mode, continuous, mechanical tuning range of 73.2 nm with high output power and low threshold current performance, which is suitable for next generation swept-source optical coherence tomography (OCT) imaging and sensing applications.**

Keywords—Vertical-cavity surface-emitting laser, Optical Coherence Tomography, Optical microelectromechanical (MEMS) devices, tunable lasers, wide tuning range.

I. Introduction

High-speed, swept-source optical coherence tomography (SS-OCT) is a rapidly emerging ophthalmologic technique with higher resolution than previous OCT techniques [1-2]. The key enabling component of this technique is a single mode laser with a wide, mode-hop-free tuning range exceeding 70 nm and 100 kHz to 1+ MHz tuning repetition rate of the laser diode. The initial reports of this technique used optically-pumped MEMS-tunable VCSELs [2], which are considerably more costly, bulky, and complex to fabricate than conventional electrically-pumped VCSELs. Electrically-pumped MEMs tunable VCSELs have steadily matured in recent years [1, 3-5] but had not yet been realized with a mechanical tuning range exceeding 70 nm, desired for commercial applications. We demonstrate in this paper a laser with a single longitudinal-mode cavity that operates mode-hop-free throughout its entire mechanical tuning range, with a minimum acceptable output power and threshold current across the entire tuning range. We package the tunable VCSEL in a TO-can, making it fully suitable for commercial applications. Here we present the details of the experimental results of our MEMs tunable VCSELs performance emitting at the tuning range center of 1030 nm and show the potential increase to 100+ nm tuning range.

II. Tuning Range Performance of MEMS Tunable VCSELs

We use a GaAs-based material system for our MEMs VCSELs, a high-contrast grating (HCG) layer as a top DBR mirror along with an active region and bottom DBR mirror on a GaAs substrate. The HCG is a single layer of high refractive index material, which exhibits high reflectivity across a tuning range of 100+ nm. The wavelength tuning is accomplished by applying a reverse bias voltage between the p-DBR and suspended HCG, causing the HCG to actuate downwards towards the body of the VCSEL. The structure is fabricated by metal-organic chemical vapor deposition (MOCVD). The active region incorporates multiple compressively-strained InGaAs QWs surrounded by InGaP barriers. Doped and graded GaAs/AlGaAs DBRs are used for the bottom mirror, consisting of ~25-30 pairs. The mirror design has been optimized for a wider mode-hope free tuning range compared to previous work [3].

The semiconductor-air reflection of our MEMs tunable VCSELs is designed to be out of phase with the semiconductor cavity. This configuration is an air-cavity-dominant (ACD) design [3], where the optical field is confined more significantly in the air cavity at the center design wavelength.

The fabrication of our tunable VCSEL is similar as reported in [3-4], with the fabrication process modified so the device can be packaged in a TO-can. Wet oxidation is used for electrical current confinement. The investigated VCSEL had a nominally 8-um diameter measured oxide aperture size.

The calculated tuning range is shown for two different structure designs in Fig. 1, where the threshold material gain as a function of the tuning wavelength is shown, including the intrinsic losses. The red design, experimentally realized in Fig. 2, has a calculated 78 nm tuning range. The blue design has an optimized mirror-cavity design with an expected 108 nm tuning range and is under fabrication. The threshold gain of the current (red) design is slightly higher

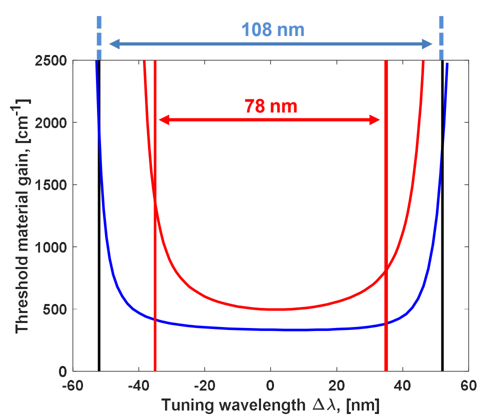

Fig. 1. The threshold material gain as function of the tuning wavelength for the currently investigated VCSEL design (red) and a new optimized design still under fabrication (blue), including the intrinsic losses.

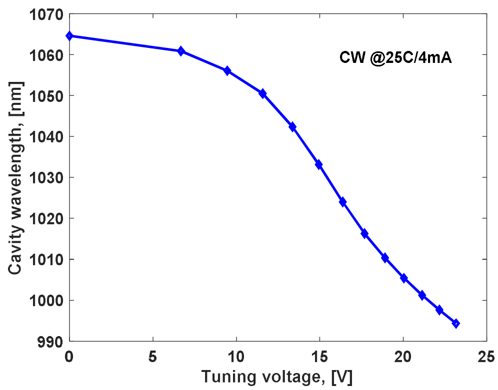

Fig. 2. Measured cavity wavelength at 25°C and 4 mA of the MEMs tunable VCSELs versus tuning voltage for the red design.

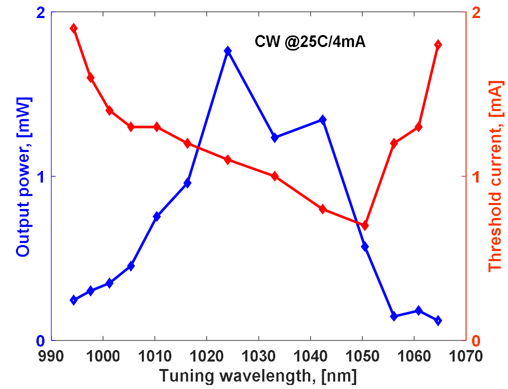

Fig. 3. Output power peak and threshold current responses of the MEMs VCSEL device at 25°C and I=4mA.

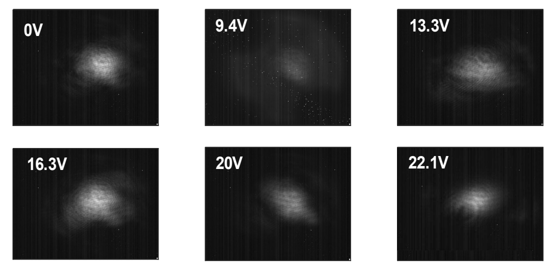

Fig. 4. Measured far field patterns at different tuning voltages at 25°C and I=4mA.

than the optimized design (blue) at the tuning center. In the new structure, we have optimized our tunable VCSEL design structure to have a wide single mode continuous tuning range of ~108 nm with high wavelength sweep speed, which allows for even higher resolution OCT target applications.

The measured cavity wavelength characteristics of our processed devices as a function of the tuning voltage is shown in Fig. 2. The device exhibits strongly single mode operation at 4mA and 25°C at all tuning voltages resulting in a record single-mode, continuous mechanical tuning range of 73.2 nm, achieved by a DC bias externally applied tuning voltage up to 23 V. Our test results are close to what is expected based on our calculation, where a theoretical tuning range of 78 nm is predicted for this VCSEL structure. The device is centered at 1030 nm here instead of 1050 nm due to inadvertent shifts in epitaxial layer thicknesses during epitaxial growth. The tuning voltage reported in this paper is relatively small compared with other MEMS structures in VCSELs [1, 3].

The laser diode operating voltage with no tuning is 4 V obtained at 5mA and 25°C indicating a series resistance of around 250 Ω which is very close to the forward voltage reported in [1].

We also measured the maximum output power and the threshold current characteristics of our tunable VCSELs at 25°C and 4mA for different tuning voltages. The results are presented in Fig. 3. Across the full tuning range of 73.2 nm, we demonstrate a minimum output power of 0.12 mW and a maximum threshold current of 1.9 mA. By increasing the tuning voltage, a maximum of 1.8 mW output power and a minimum of 0.7mA threshold current are achieved around the tuning center, suitable for OCT applications across the entire tuning range.

In addition, we performed far field measurements at 4mA and 25°C for several different tuning voltages across the tuning range. In Fig. 4, we present the far field patterns for our 1050 nm tunable VCSEL at several different tuning voltages. We demonstrate single mode and single lobe operation at all tuning voltages across the full tuning range.

In summary, we present a high performance, widely and continuously tunable, electrically-pumped VCSEL at 1050-nm wavelength center with low DC bias voltage.

To the best of our knowledge, this is a record value for an electrically-pumped tunable VCSEL. The device reported here is suitable for next generation swept source OCT applications.

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