Single-Mode and High-Speed 850nm MEMS-VCSEL

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Demis D. John[1], Byungkun Lee[2], Benjamin Potsaid[2,3], Amanda C. Kennedy[1], Martin E. Robertson[1], Christopher B. Burgner[1], Alex E. Cable[3], James G. Fujimoto[2], Vijaysekhar Jayaraman[1]
[1]*Praevium Research Inc., 5385 Hollister Avenue, Santa Barbara, CA 93111, U.S.A.*
[2]*Massachusetts Institute of Technology, Dept. of Electrical & Computer Engineering, 50 Vassar St., Cambridge, MA 02139, U.S.A.*
[3]*Thorlabs Inc., 56 Sparta Ave., Newton, NJ 07860, U.S.A.*
Author e-mail address: demis@praevium.com

Abstract: We present an 850nm Vertical-Cavity Surface-Emitting Laser (VCSEL) with electrostatically-actuated top mirror. Developed to target the water-transmission window for ophthalmic imaging, the light source achieves 37.7nm of tuning at 347kHz unamplified, and 5.4mW amplified power.
OCIS codes: (140.3600) Tunable lasers; (140.7260) Vertical cavity surface emitting lasers

1. Introduction

Research on new light sources for the medical imaging technique known as Optical Coherence Tomography (OCT) has been very active in recent years. Prototype light sources previously relegated to the lab are being developed as commercial OCT swept-sources, often targeted to specific medical imaging applications. Ophthalmology, being one of the most significant OCT markets, has spurred much of this interest in new light sources.

The MEMS-Tunable VCSEL (Microelectromechanically-Tunable Vertical-Cavity Surface-Emitting Laser) has significant advantages for OCT due to the single-mode (both transverse & longitudinal) and mode-hop free tuning, along with high-speed tuning at hundreds of kHz and long coherence lengths as compared with other popular OCT light sources [1–3]. The speed and tuning range of previously demonstrated 1310 nm & 1050 nm tunable sources with 110 nm & 100 nm optical tuning bandwidths, respectively [1,4], has enabled numerous advances in endoscopic & ophthalmic imaging [5–7].

The wavelength of light sources for ophthalmic OCT is primarily chosen to target a region of the water absorption spectrum in which there is low optical loss. Our MEMS-VCSEL sources at 1050nm were chosen to target the low-loss 1060nm region in the water absorption spectrum, as shown in Figure 1.

A near-IR swept-source in the low-absorption 850nm region may enable better resolution compared to 1050nm, in addition to the possible imaging-range benefit of swept-source OCT versus the more common spectral domain (broad-band source) OCT. These reasons have motivated the development of a new 850nm MEMS-VCSEL intended for ophthalmic OCT imaging that we present for the first time in this paper.

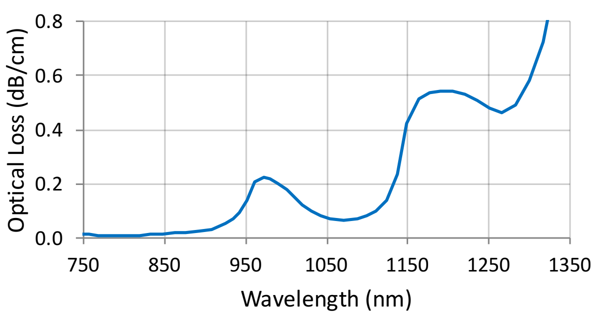

Fig. 1: Water Absorption in the near-IR from [8].

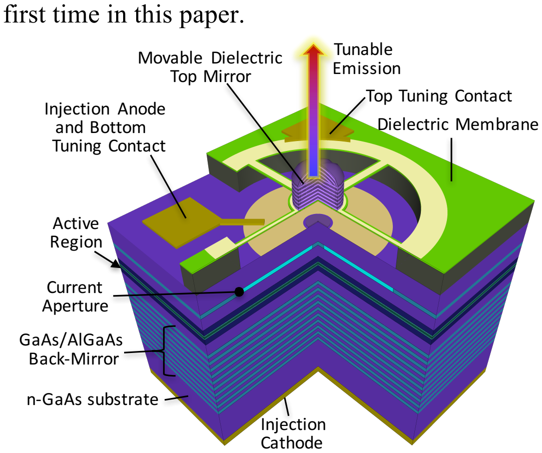

Fig. 2: Schematic of the 850nm MEMS-VCSEL.

2. Design

The core MEMS wavelength-tuning component of previous devices is extensible to other wavelength ranges and the GaAs-based materials used in our 1050nm MEMS-VCSELs is easily extended into the 850nm range. A P-i-N diode structure was grown with a standard GaAs/AlGaAs back mirror, as schematically shown in Figure 2. Targeting single-mode operation, we fabricated devices with thermally-oxidized current apertures, formed by converting the as-grown AlAs current-aperture layer into AlO_x, leaving an unoxidized aperture diameter varying from 2-7µm. A metal contact on the p-type GaAs surface of the semiconductor acts as the laser injection anode and funnels current through the unoxidized portion of the current aperture into AlGaAs quantum wells. Finally, current exits through the back mirror and n-GaAs substrate, to a laser injection cathode on the substrate underside.

The Injection Anode also acts as the MEMS bottom contact. Since the MEMS draws negligible current, it is possible to apply an AC or DC voltage between the MEMS bottom & top contacts, constricting the air gap and tuning the cavity mode, while simultaneously applying a DC current to the laser injection contacts without the two signals interacting significantly. The top-half of the cavity was completed similarly to our previous devices described in [1] and [4].

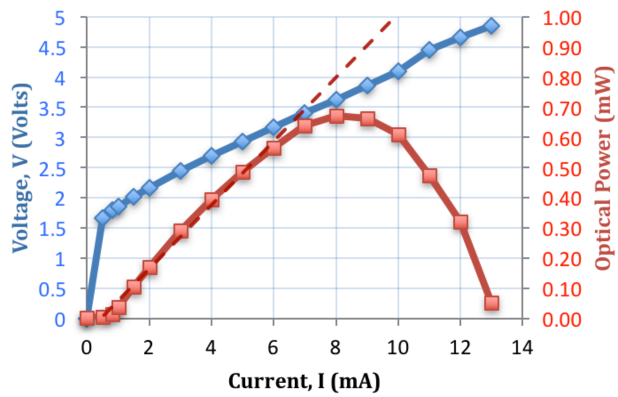

Fig. 3: L-I-V curves show a threshold laser current of 0.79mA at a rest wavelength of 850.2nm, and a maximum optical power of 672µW.

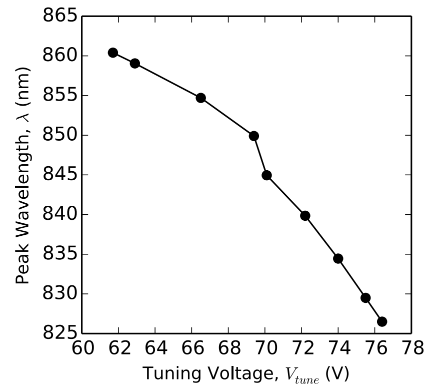

Fig. 4: Peak wavelength vs. Tuning Voltage

3. Optical Testing Results

Previous researchers have shown MEMS-VCSELs operating at 850nm targeting optical communications [9,10]. The previous work achieved 19nm, and later 37nm, of tuning at a tuning speed of 0.70kHz with thermal tuning of the MEMS. These devices lased in multiple lateral modes, with about 0.4mW of output power. Targeting OCT instead, we have applied our electrostatic MEMS technology to address the requirements of high-tuning speed, single-mode operation and wide bandwidth. In addition, higher output power is required for ophthalmic imaging.

First-generation devices exhibit a thermal rollover at 672µW, as shown in Fig. 3. The devices are single-lateral-mode up to 6mA with ≥38dB SMSR (side-mode suppression ratio), above which a second-order lateral mode begins to lase. Figures 4 & 5 show the tuning range at 4mA laser current, with 36.0nm of continuously-swept tuning (-6dB) at 429kHz (dark green) in a single longitudinal mode. By reducing the airgap further, the device switches into a second longitudinal mode, as shown in the double-peaked 61.7V discrete spectrum of Fig. 5. Electrostatic softening reduces the stiffness of the membrane and decreases the resonance frequency for this tuning range, resulting in 37.7nm of continuous single-mode tuning at 347kHz (light green) for a 6mA laser current. The spectra in Fig. 5 were acquired with 200µm-core multi-mode optical fibers to capture any lateral modes, while a single-mode fiber (SMF) coupled device showed a slightly improved SMSR of 43dB. All devices operate in a single polarization.

Mode profiles were acquired at the rest-wavelengths (V_{TUNE} = 0.0V) of various unpackaged devices in the same production run with a Thorlabs M2MS-BP209IR measurement system, the results of which are shown in Fig. 7.

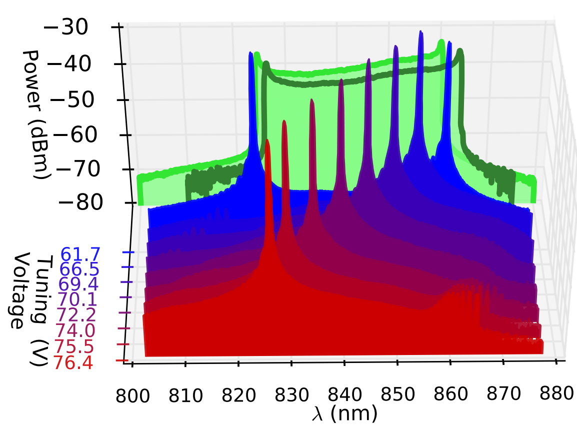

Fig. 5: The devices tune 36.0nm in the 1st longitudinal mode (light green), and 37.7nm in the 2nd longitudinal mode (dark green) at 4mA & 6mA laser currents, respectively.

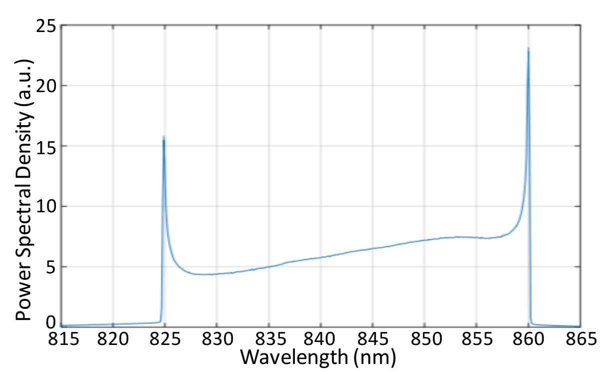

Fig. 6: Spectrum of 400kHz dynamic tuning amplified by an SOA, with 5.38mW optical power output at 96mA and 53% pulse-width modulated duty cycle.

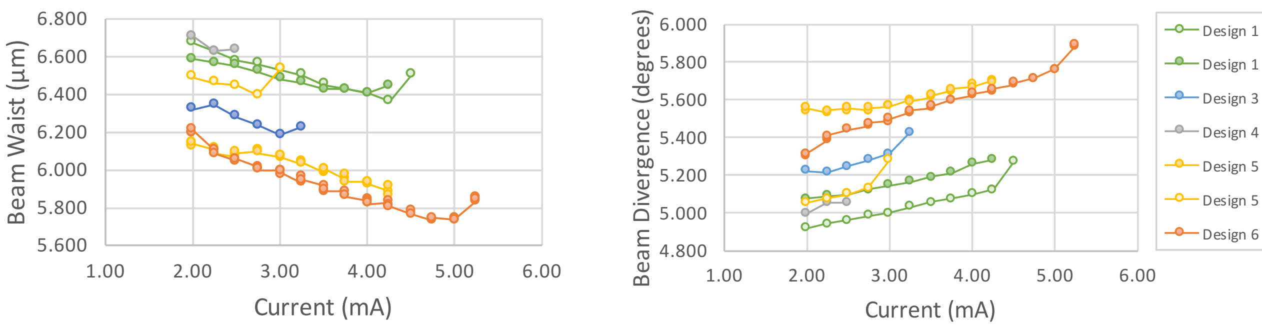

Fig. 7: Beam Waist (diameter) and Beam Divergence (half-angle) versus Laser Current, for various devices from the same run.

In Fig. 7, each design represents a current-aperture size variation of nominally 0.25µm, with Design 1 being the largest, although the actual aperture size has some deviation from the nominal design. The sudden uptick at higher currents corresponds to a reduced beam measurement quality, likely due to higher-order lateral modes. Beam waist diameters vary between 5.7–6.7µm, with decreasing waist versus laser drive current, while beam divergence half-angles range from 4.9–5.9° with increasing divergence versus laser current.

The optical power must be amplified in order to take full advantage of the OCT optical power limits. Although few commercial wide-band SOAs (semiconductor optical amplifiers) are available in the 850nm range, our device is well-matched to the Superlum SOA-352. A MEMS-VCSEL packaged with SMF was amplified with the aforementioned SOA, with AC Photonics isolators on either side of the SOA, resulting in an amplified optical power of 5.38mW for a 400kHz sweep. Figure 6 shows the amplified spectrum with a 96mA SOA current which is pulse-width modulated with a 53% duty cycle to output only a single sweep direction as a light source suitable for OCT.

4. Conclusions

We have shown an 850nm MEMS-VCSEL with single-mode tuning over 37.7nm at high sweep speeds of 350–430kHz, with up to 670µW of unamplified optical power, and a fiber-coupled side-mode suppression ratio of 43dB. When utilized with a matched amplifier, we achieved average optical powers of 5.38mW at 400kHz sweep rates in a single-scan direction.

This new 850nm swept-source will be applied to ophthalmic OCT imaging in a future publication.

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