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Reliable Widely Tunable Electrically Pumped 1050nm MEMS-VSCSELs with Amplifier in Single Butterfly Co-Package

Christopher Burgner*[a], John Carter[a], Alan Donaldson[d], Nate Bramham[a], Benjamin Potsaid[b,c], Oscar Carrasco-Zevellos[c], Siyu Chen, Eric Moult[c], James G. Fujimoto[c], Peter Heim[d], Vijaysekhar Jayaraman[a], Alex Cable[b,d]
[a]Praevium Research Inc., Santa Barbara CA 93117; [b]Advanced Imaging Group, Thorlabs, Inc., Newton NJ 007860; [c]Department of Electrical Engineering and Computer Science and Research of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139; [d]Thorlabs Quantum Electronics Inc., Jessup, MD 20794

ABSTRACT

We demonstrate the first 1050nm MEMS-eVCSEL co-packaged with a wideband amplifier to achieve over 70nm wavelength tuning at over 30mW of output power and SMSR greater than 40dB. Ophthalmic Optical Coherence Tomography Angiography (OCTA) images acquired at 800kHz A-scan rates showcase the telecom grade 14pin butterfly co-package as a path to low cost swept source OCT engines. Device design employs a strain-compensated InGaAs/GaAsP gain region disposed on a wideband fully oxidized GaAs/AlxOy back mirror capable of tuning ranges beyond 100nm. It has been suggested the wideband fully oxidized GaAs/AlxOy back mirror may pose risk to device lifetime reliability. However, over 9000hrs of lifetime testing validates reliability and projects device lifetimes exceed 20,000hrs under continuous use.

Keywords: Tunable VCSEL, Swept source, OCT, Optical Coherence Tomography,

1. INTRODUCTION

Stimulated by the telecommunications revolution of the 1990s, early development of MEMS-Tunable VCSELs focused on wavelengths centered around 650nm[1], 850nm[2], 970nm[3,4], and 1550nm[5]. The optically pumped 1550nm MEMS-VCSEL work by Coretek, Inc. first introduced a co-package scheme which integrated a hermetic package containing the 1550nm MEMS-VCSEL, 1310nm pump laser, broadband wavelength locker and power monitor[5]. By the late 1990s, swept source optical coherence tomography (SS-OCT)[6] created a new demand for a fast wavelength tunable light source wavelengths suited for deep imaging of biological material.

MEMS-tunable VCSELs at 1050nm have emerged as a high performance swept light source for ophthalmic optical coherence tomography. Optically pumped 1060nm MEMS-oVCSELs have achieved 100nm of tuning range[7], sweep adjustability to enable multi-modal OCT imaging[8], and retinal imaging at over 1MHz A-scan rates[9]. Monolithically wafer fabricated, electrically pumped MEMS-eVCSEL technology has powerful advantages over MEMS-oVCSELs by eliminating the pump laser, avoiding the need to bond individual MEMS dies to ½ VCSELs, and enabling full wafer level test. Electrically pumped 1060nm MEMS-eVCSELs have achieved 63nm tuning range, 400kHz A-scan rate retinal imaging, and an estimated ~200m coherence length[10]. Previous demonstrations of ophthalmic imaging with MEMS o-VCSELs and e-VCSELs have required external optical amplifiers. A recent publication has shown co-packaging of a pump laser, o-VCSEL, and semiconductor optical amplifier in a 14 pin butterfly package to achieve 75nm of tuning at up to 100kHz sweep repetition rate with 50mW of output power[11].

*chris@praevium.com; phone 1-805-964-2463; www.praevium.com

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In this work, we demonstrate the first 1050nm MEMS-eVCSEL co-packaged with a wideband optical amplifier in a single butterfly package. e-VCSELs can be manufactured at substantially lower cost and higher volume than o-VCSELs. Our devices achieve over 70nm wavelength tuning at over 30mW of output power and SMSR greater than 40dB. We describe the device, co-package, and show initial ophthalmic OCT and OCTA images. We also demonstrate MEMS-eVCSEL technology that achieves ~100nm tuning range and lifetime reliability results over 9000 hours (375 days) of continuous operation. Combined, these technologies will enable a new generation of low cost, miniature, environmentally stable, co-packaged MEMS-eVCSEL OCT light sources with MEMS-oVCSEL levels of performance.

2. DEVICE AND CO-PACKAGING

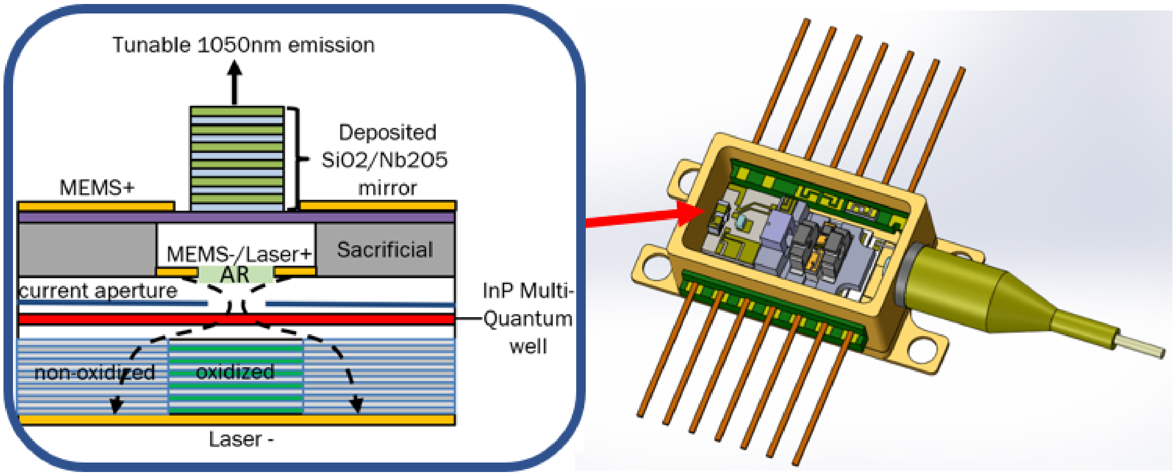

Figure 1. A. Electrically pumped MEMS-eVCSEL structure with suspended dielectric top mirror on a monolithically fabricated MEMS. The three device contacts enable electrostatic wavelength tuning and injecting current through a lithographically defined current aperture. This is all built on a multi-quantum well grown on fully oxidized $GaAs/Al_xO_y$ back mirror. B. The arrow shows the MEMS-eVCSEL in the co-package behind the lenses, optical isolator and amplifier, before coupling into a single mode fiber.

Figure 1A shows our device design that employs a strain-compensated InGaAs/GaAsP gain region deposited on a wideband fully oxidized $GaAs/Al_xO_y$ back mirror. A deposited multilayer dielectric top mirror rests on a flexible dielectric membrane separated by a variable airgap from the underlying gain region. The device is fully monolithically fabricated, requiring no MEMS die bonding, an important consideration in manufacturability. The air gap is created by a sacrificial layer that can be removed before die singulation which allows for laser performance testing at wafer level. Application of voltage between the dielectric membrane and a bottom actuator contact on the top of the gain region creates an electro-static force which pulls the suspended mirror down, contracting the airgap and tuning the device to shorter wavelengths. The short, micron-scale cavity enables single-longitudinal mode operation across a wide tuning range without mode-hops. In this 3-terminal device, the bottom actuator contact doubles as the laser anode. Current injection proceeds from the anode to cathode at the back of the GaAs substrate through a lithographically defined low-loss current aperture, enabling reproducible aperture size and reproducible single-mode performance.

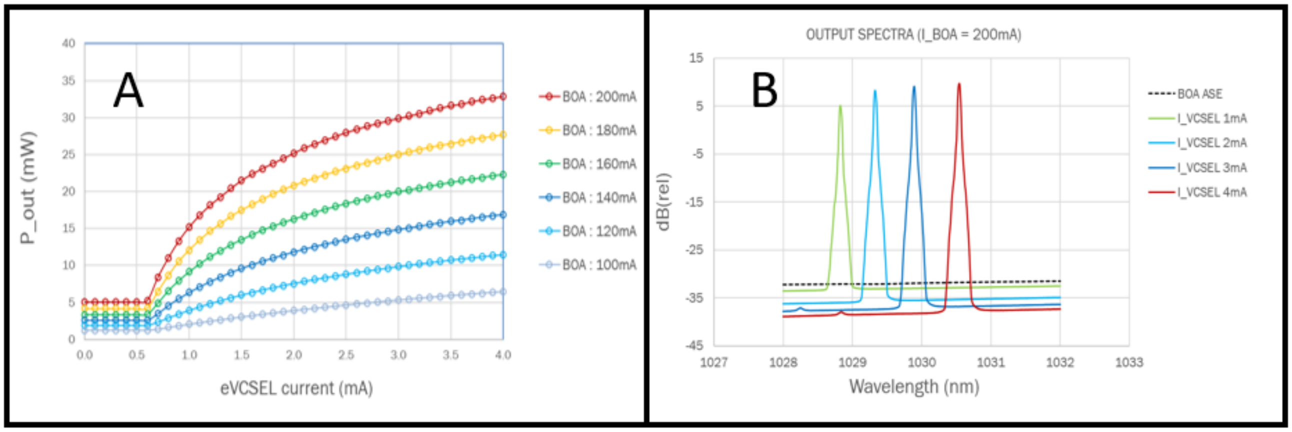

Figure 2. A. Output power with booster optical amplifier (BOA) currents from 100mA to 200mA and eVCSEL L-I curves over 0-4mA of drive current, demonstrating over 30mW output power from a single mode fiber. B. Static spectra at 4mA of eVCSEL drive current. Side mode suppression ratios of greater than 40dB are observed.

Elimination of an external optical amplifier is achieved by integrating both the electrically pumped MEMS-eVCSEL and optical amplifier into a single standard 14 pin telecom grade butterfly package, schematically shown in Figure 1B. The MEMS-eVCSEL, lenses, isolator and optical amplifier (BOA) all rest on a thermally controlled platform and are aligned using high-volume-ready standard telecom laser weld packaging techniques. Figure 2A shows the optical performance of the MEMS-eVCSEL amplifier co-package. Heat is sufficiently removed from the BOA to allow for 200mA drive currents which generate optical powers greater than 30mW at an eVCSEL drive current of 4mA. MEMS-oVCSELs optically pumped by a Gaussian beam have an intrinsic side mode suppression ratio (SMSR) advantage over eVCSELs which suffer from a non-Gaussian current injection profile. Figure 2B demonstrates single mode lasing at a current injection amplitude up to 4mA. The side mode suppression ratios SMSR (>40dB) are well matched to ophthalmic imaging requirements.

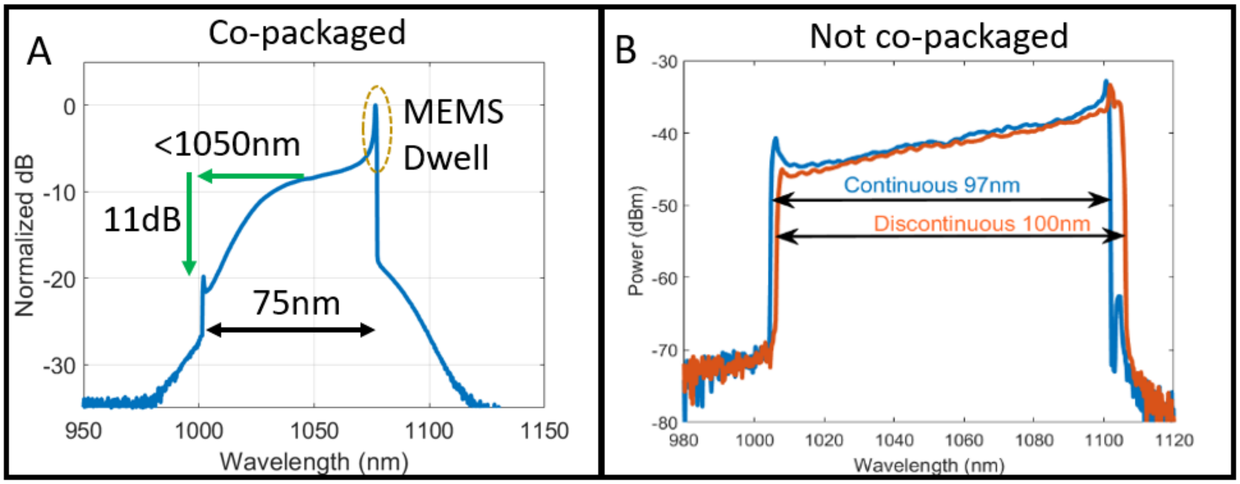

Figure 3. A. 75nm of co-packaged tuning range demonstrated. Power spikes near the edges are due to MEMS dwell. Rapid decrease in power below 1050nm is believed to be due to isolator losses. B. In a recent non co-packaged tunable device, ~100nm of tuning range is achieved due to the ultra-wide oxidized back mirror bandwidth.

A co-packaged eVCSEL was tuned dynamically and the time averaged spectrum was captured in Figure 3A. The device was driven using a sinusoidal voltage waveform. Due to the electrostatic actuation, the resulting wavelength trajectory resembles a sinusoid with more time spent at longer wavelengths. In a time averaged spectrum, the MEMS dwells when it reverses wavelength scan direction and is seen in the spikes near the edges of the tuning range. The sharp drop in power amplitude below 1050nm is partially created by the increased velocity of the wavelength trajectory due to the quadradic nature of the MEMS electrostatic actuation. Additionally, the isolator used in this co-packaged design was characterized to have over 7dB of loss between 1050nm and 1000nm. Figure 3B shows results from a recent ~100nm MEMS-eVCSEL device which has not been co-packaged. The device in Figure 3B does not show the rapid decrease in optical power below 1050nm due to the isolator present in Figure 3A. The high index contrast provided by a fully oxidized GaAs/Al_xO_y back mirror enables monolithically fabricated MEMS-eVCSELs with tuning ranges >100nm, achieving better performance than un-oxidized AlGaAs/GaAs back mirrors which limit tuning bandwidth[11].

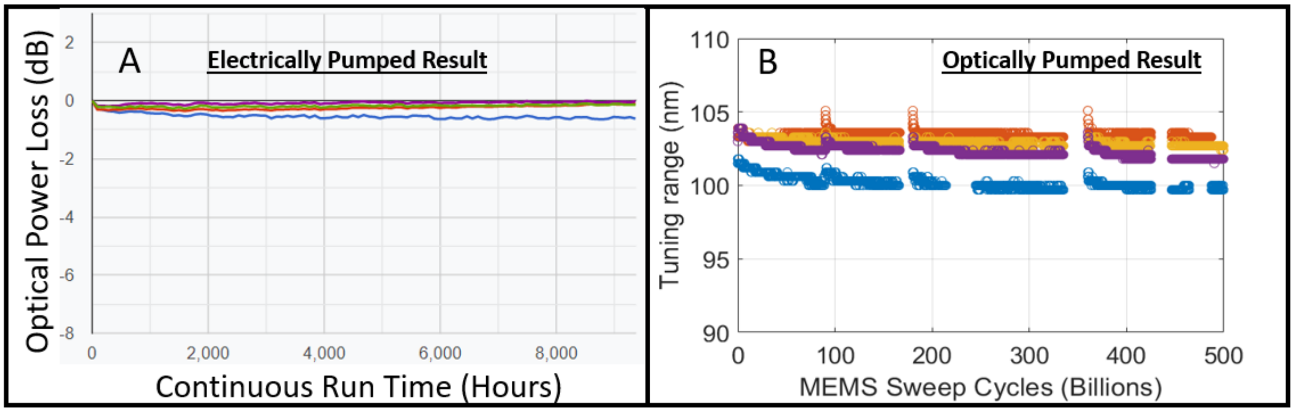

Figure 4. A. 9,000 hour test of 8 fixed wavelength devices with GaAs/Al_xO_y mirror with drive current set to 4mA producing ~700uW of single mode 1060nm emission. Less than 0.5dB of power loss was observed over the 9,000hrs. B. The same MEMS moving mirror is used on both MEMS-eVCSELs and MEMS-oVSELs. The MEMS mirror is cycled over 500 billion times.

It has been suggested the wideband fully oxidized GaAs/Al_xO_y back mirror may affect device lifetime and reliability[11]. To investigate this, electrically pumped eVCSELs were fabricated using fully oxidized back mirrors and placed into reliability racks where their current was set to a constant 4mA, producing roughly 700uW of single mode 1060nm output power. The temperature was maintained at 25 degrees Celsius and optical power was measured at 10 minute intervals. Figure 4A shows over 9000hrs of lifetime testing at a single wavelength, demonstrating reliability, with projected device lifetime exceeding 20,000hrs of continuous use. The monolithic fabrication process for the MEMS-oVCSEL is the same as the process of the MEMS-eVCSEL. Figure 4B shows the wide tuning range achieved by a MEMS-oVCSEL cycled over 500 billion times which utilizes the same MEMS design as the MEMS-eVCSEL.

3. OCT IMAGING

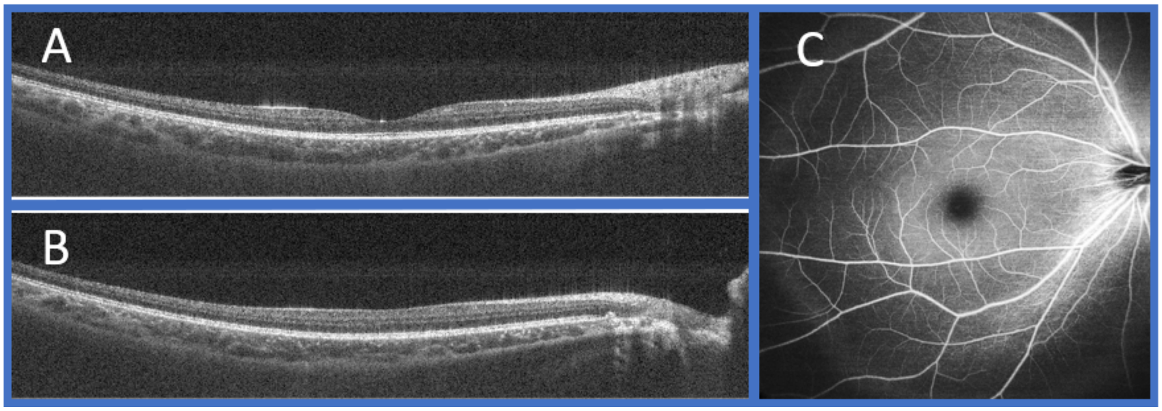

Figure 5. OCT imaging performed using MEMS-eVCSEL and co-package amplifier device at 800kHz A-scan rate. A. Single OCT cross sectional image of a normal human retina through the fovea (900 A-scans over 11mm). B. Single OCT cross sectional image of the human retina through the optic nerve head (900 A-scans over 11mm). C. OCT Angiography (OCTA) image of the human retina showing retinal vasculature (900x900 A-scans over 11mmx11mm).

Elimination of the pump laser, reduction in component size, and the high volume packaging platform yields lower costs and will enable new OCT applications which are otherwise price prohibitive, including personal OCT systems for in-home ophthalmic monitoring. To demonstrate the co-packaged MEMS-eVCSEL, we performed ophthalmic OCT imaging at 800kHz A-scan rates. Figure 5 shows OCT cross sections (Fig. 5A-B) and en face OCT angiography (OCTA) (Fig. 5C). The OCTA imaging demonstrated at 800kHz in this work is between 5x-10x faster than the leading commercially currently available.

4. SUMMARY

A wide tuning range and high speed co-packaged MEMS-eVCSEL / optical amplifier in a telecom grade 14 pin butterfly co-package promises to be an enabling technology for both low cost and high performance ophthalmic OCT. Recent MEMS-eVCSELs rival 100nm tuning ranges previously only attainable in optically pumped VCSELs. This technology can be extended to other wavelengths enabling applications beyond ophthalmology. The capability of MEMS-eVCSELs to achieve variable sweep repetition rates into the MHz regime with long coherence lengths promises to enable applications in endoscopy, metrology, and LIDAR, as well as personal OCT.

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