High-sweep-rate 1310 nm MEMS-VCSEL with 150 nm continuous tuning range

V. Jayaraman, G.D. Cole, M. Robertson, A. Uddin and A. Cable

Microelectromechanical-systems-based vertical-cavity surface-emitting lasers (MEMS-VCSELs) capable of a 150 nm continuous tuning range near 1310 nm are demonstrated. These devices employ a thin optically pumped active region structure with large free-spectral range, which promotes wide and continuous tuning. To achieve VCSEL emission at 1310 nm, a wide-gain-bandwidth indium phosphide-based multiple quantum well active region is combined with a wide-bandwidth fully oxidised GaAs-based mirror through wafer bonding, with tuning enabled by a suspended dielectric top mirror. These devices are capable of being scanned over the entire tuning range at frequencies up to 500 kHz, making them ideal for applications such as swept source optical coherence tomography and high-speed transient spectroscopy.

Introduction: MEMS-VCSEL development has primarily focused on communications and low-speed spectroscopic applications. Because of the narrow line-width, continuous singlemode tuning, monolithic fabrication, and high-speed tuning capability of these devices, MEMS-VCSELs are an attractive optical source for emerging swept source optical coherence tomography (SS-OCT) systems and high-speed transient spectroscopy applications. SS-OCT systems targeting vascular and cancer imaging applications require >100 nm of tuning near 1310 nm. Prior to 2011, there were no reports of integrated MEMS-VCSELs in the 1310 nm range, and the widest reported tuning range at any wavelength was 65 nm at 1550 nm [1]. The first 1310 nm VCSELs with the requisite >100 nm range for SS-OCT were demonstrated by our group along with collaborators in [2]. The results presented in this Letter showed record OCT imaging rates with excellent image quality. Around the same time, >100 nm of tuning was also reported for the first time near 1550 nm [3].

In this Letter, we demonstrate further expansion of the tuning range near 1310 nm to a current record value of 150 nm, by employing a thin, wide-FSR cavity design. Moreover, through careful design of the electrostatic actuator, this tuning range can be continuously covered at 500 kHz repetition rates. These devices are extremely promising not only for application in SS-OCT, but also in transient spectroscopic applications such as combustion monitoring or engine thermometry [4].

Device structure and fabrication: Fig. 1 illustrates a three-dimensional cutaway view of the device employed in this work. The laser cavity employs a thin wide-gain InP-based multi-quantum well (MQW) active region joined by wafer bonding to a wideband bottom GaAs-based fully oxidised Al_xO_y-GaAs mirror, with tuning enabled via the integration of a dielectric micromechanical actuator similar to that presented in [5]. In this configuration, the top dielectric mirror is separated from the underlying 'half-VCSEL' structure by an air-gap which is tuned by electrostatic actuation. The VCSEL is optically pumped at 980 nm through the suspended mirror, generating tunable 1310 nm emission, which emerges from the same side of the device. Though the schematic of Fig. 1 shows four supporting struts, a variety of actuator geometries have been fabricated.

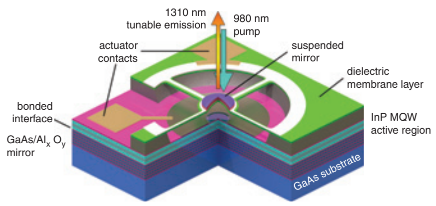

Fig. 1 *Solid model of device structure employed in this work, combining wide-bandwidth long-wavelength active region with optimised tunable microcavity*

Several features of our microcavity design promote a wide tuning range. First, the optically pumped configuration eliminates the need for doping of the mirrors and cavity, significantly reducing free-carrier absorption, which in turn reduces the threshold gain and enables lasing over a wider portion of the gain spectrum. The optically pumped structure also eliminates resistive heating, further increasing the available gain. Additionally, optical pumping removes the need for thick current spreading layers, minimising the total cavity length and extending the FSR, which ultimately limited tuning in previous devices [2, 3]. Lastly, the incorporation of wideband mirrors and the wideband gain spectrum possible with InP-based MQW structures also promotes ultra-wide tuning.

Static and dynamic tuning results: Fig. 2 displays the test setup used to obtain the tuning results presented in the subsequent Figs. 3 and 4. A single cleaved and antireflection coated optical fibre is coupled to the VCSEL cavity, delivering incoming pump light at 980 nm and also collecting the emitted tunable VCSEL radiation near 1310 nm. A WDM coupler separates the incoming pump light from the VCSEL emission, with the latter sent to an optical spectrum analyser (OSA) for characterisation of the tuning range. Both static and high-speed time-dependent tuning voltages are applied via a high-voltage (HV) amplifier, which is driven by an arbitrary waveform generator.

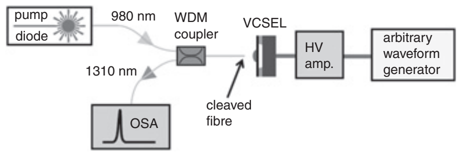

Fig. 2 *Schematic illustrating cleaved fibre coupling scheme as well as separation of incoming/outgoing light by WDM coupler*

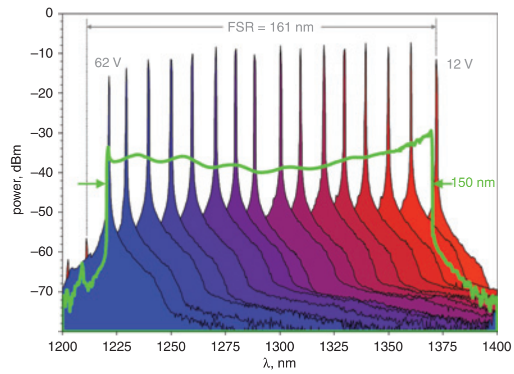

Fig. 3 *Static and dynamic tuning response of our ultra-widely tunable MEMS-VCSELs*

The long-wavelength (red) spectrum at 1372 nm exhibits a competing mode at 1211 nm, illustrating the 161 nm FSR of the cavity. The green curve represents the time-averaged spectrum under sinusoidal sweeping at 500 kHz. Both the static and the dynamic response demonstrate continuous single-transverse and longitudinal mode lasing operation over a 150 nm span. The ripple in the integrated spectrum is due to the residual reflectance of the cleaved delivery fibre

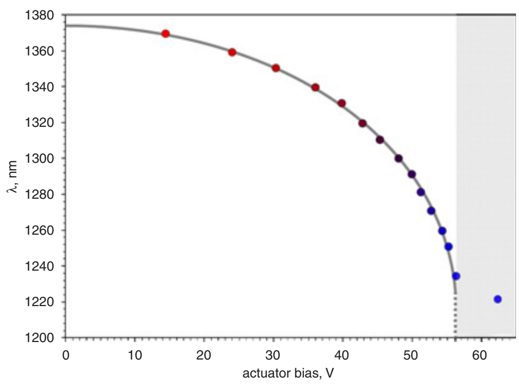

Fig. 4 *Emission wavelength against static tuning voltage for device shown in Fig. 3*

Theoretical curve based on work presented in [6]. Shaded region beyond 56 V indicates unstable regime for actuator

Figs. 3 and 4 illustrate both the static and the dynamic tuning properties of these VCSELs. In Fig. 3, the optical spectrum at an applied bias of ~12 V is shown as the right-most red spectrum in the Figure. This spectrum shows laser emission at 1372 nm along with a competing mode at 1211 nm, yielding a 161 nm FSR for these devices. Application of a static voltage up to ~56 V pulls the mode across a stable and continuous static tuning range exceeding 140 nm, illustrated by the static tuning response in Fig. 4. Higher applied biases enable further tuning to 1222 nm (covering a 150 nm range), though biases beyond ~56 V exceed the snapdown voltage of the device.

For deployment in SS-OCT or other repetitively scanned applications, the dynamic, rather than static, tuning range is the key figure of merit. The green curve of Fig. 3 shows the time-averaged optical spectrum under sinusoidal sweeping at 500 kHz. Under repetitive sweeping conditions, the static snapdown voltage can be reliably exceeded owing to inertial overshoot of the suspended mirror, resulting in full utilisation of the 150 nm tuning range. For SS-OCT, which can employ bidirectional scanning, the 500 kHz repetition rate enables an axial scan rate of 1 MHz, which is far faster than any competing laser previously employed in SS-OCT and similar to that obtained with our narrower tuning-range MEMS-VCSELs reported previously [7]. These devices employ a similar actuator design, which provides flat frequency response, variable rate operation, and linearisation of wavelength trajectories through arbitrary waveform pre-shaping of the drive waveform [7].

Conclusion: We have demonstrated the widest tuning range of any MEMS-VCSEL at any emission wavelength, enabled by a wide FSR micro-cavity, wideband gain spectrum, and wideband mirrors combined in an optically pumped configuration. The low mass suspended mirror structure enables tuning rates of 0.5 MHz with a flat frequency response, allowing for variable sweep rates spanning DC to 1 MHz (exploiting bidirectional scanning). In SSOCT systems, increased tuning range translates directly into improved imaging resolution [8]. These devices therefore promise to enable a new generation of high-speed, high resolution OCT imaging systems, and pave the way for new applications in high-speed transient spectroscopy.

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One or more of the Figures in this Letter are available in colour online.

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