Rapidly swept, ultra-widely-tunable 1060 nm MEMS-VCSELs

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Demonstrated are 1060 nm microelectromechanical-systems-based tunable vertical-cavity surface-emitting lasers (MEMS-VCSELs) with a 100 nm continuous tuning range under repetitively scanned operation at rates beyond 500 kHz and a 90 nm continuous tuning range under static operation. These devices employ a thin strained InGaAs multiple quantum well active region integrated with a fully oxidised GaAs/Al_xO_y bottom mirror and a suspended dielectric top mirror. The devices are optically pumped via 850 nm light. These ultra-widely tunable lasers represent the first MEMS-VCSELs reported in this wavelength range, and are ideally suited for application in ophthalmic swept-source optical coherence tomography.

Introduction: Over the past two decades, MEMS-VCSEL development has primarily focused on wavelength ranges of interest for telecommunications and spectroscopy. This has led to the demonstration of devices in the 760–780 nm band for oxygen sensing [1], near 850 nm for short-reach data communications and atomic clocks [2], at 980 nm for local area networks [3], and at wavelengths near 1550 nm for long-reach wavelength-division-multiplexed communication [4] and spectroscopy [5]. In the past year, the narrow linewidth, continuous singlemode tuning, monolithic fabrication, and high-sweep rate capability of these devices has motivated the development of widely-tunable VCSELs at 1310 nm for entirely new applications in high-speed spectroscopy and swept-source optical coherence tomography (SS-OCT) [6–8]. SS-OCT at 1310 nm is primarily employed in vascular and emerging cancer imaging applications. For ophthalmic SS-OCT, an emission wavelength near 1060 nm is preferred as it enables retinal as well as anterior eye imaging [9]. This interest has motivated the development of MEMS-tunable VCSELs at 1060 nm, following the success of similar devices for SS-OCT at 1310 nm [7, 8].

Prior to this Letter, there have been no reports of MEMS-tunable VCSELs at 1060 nm, though fixed wavelength [10] and fibre tunable devices [11] have been demonstrated in this range. Here we present the first integrated MEMS-VCSELs operating near 1060 nm, exhibiting a 100 nm dynamic tuning range (with >90 nm of tuning possible under static actuation), enabling SS-OCT coverage of the ophthalmic imaging window from 1005 to 1105 nm.

Device structure and fabrication: Fig. 1 illustrates a cross-sectional view of the device structure employed in this work. In contrast to our previous long-wavelength lasers that relied on wafer bonding to combine an InP-based active region with an oxidised AlGaAs bottom mirror [8], these lasers use a single growth step to generate a thin wide-gain-bandwidth strained InGaAs quantum well active region clad by a GaAs absorber, epitaxially grown on top of a GaAs/AlAs multilayer that is fully oxidised to produce a wideband GaAs/Al_xO_y mirror. To realise wavelength tunability, the top dielectric mirror is separated from the underlying 'half-VCSEL' by an airgap which is tuned by electrostatic actuation. Our top-emitting tunable VCSEL is optically pumped at ~850 nm through the dielectric mirror, generating tunable 1060 nm emission.

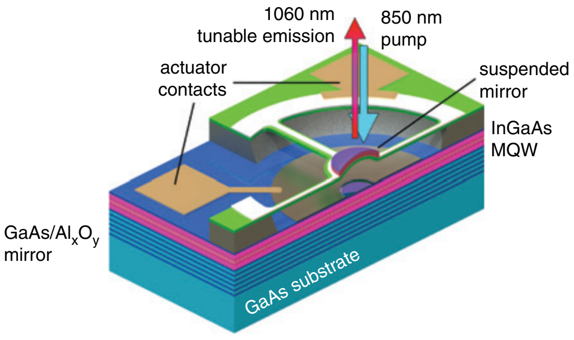

Fig. 1 *Solid model of 1060 nm MEMS-VCSEL*

Device combines epitaxial half-VCSEL (including a GaAs/Al_xO_y DBR and InGaAs active region) with a dielectric suspended mirror structure. Wavelength tuning is realised via integrated electrostatic actuator

Static and dynamic tuning results: Figs. 2 and 3 detail the tuning behaviour of a typical device. The zero voltage emission wavelength occurs at 1006 nm. Application of a small bias causes the device to switch to the longer wavelength mode at ~1105 nm. Further increases in the applied voltage blue-shift the emission wavelength to ~1010 nm before the snap-down instability at approximately 53 V inhibits further static tuning. Fig. 2 illustrates an overlay of 11 spectra covering the >90 nm static tuning range (shown in Fig. 3) of these devices, demonstrating single longitudinal and transverse mode operation over the entire span. A wavelength range of 100 nm, close to the free spectral range (FSR) of the cavity, can be accessed by dynamic tuning, as indicated by the blue curve in Fig. 2, which represents the time-averaged spectrum under repetitive sinusoidal sweeping at 200 kHz. This dynamic tuning range is the relevant wavelength span for repetitively swept SS-OCT applications.

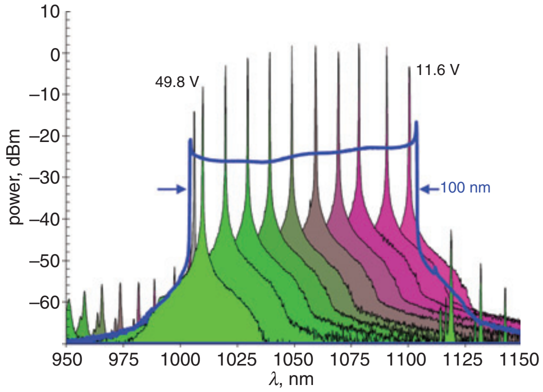

Fig. 2 *Wavelength span of continuously tunable 1060 nm MEMS-VCSEL*

Eleven spectra at various actuator biases illustrate a >90 nm static tuning range, while the time-averaged (blue) spectrum illustrates a 100 nm dynamic tuning range, under 200 kHz sinusoidal sweeping, covering nearly one FSR. Peaking of dynamic spectrum is caused by slowing of drive waveform during direction reversal

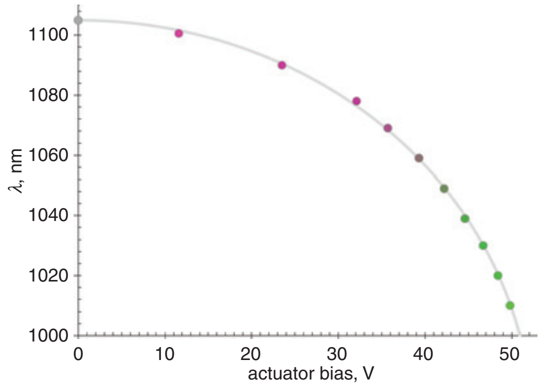

Fig. 3 *Static emission wavelength against actuator voltage for device shown in Fig. 2*

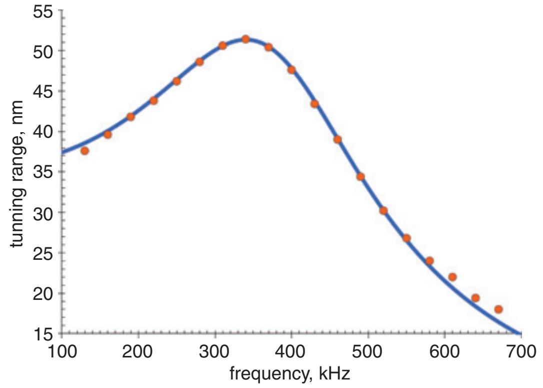

Fig. 4 *Frequency response under dynamic actuation (peak-to-peak bias of 11.6 V along with 44 V DC offset) for typical 1060 nm MEMS-VCSEL*

Theoretical curve (blue line) based on driven second-order system with undamped resonant frequency of 402 kHz and mechanical quality factor of 1.3

The average fibre-coupled output power of these devices under full dynamic tuning is near 1 mW. Ophthalmic SS-OCT requires power levels of the order of 10–15 mW, which can be achieved using semiconductor optical amplification, as has been shown successfully in 1310 nm MEMS-VCSEL-based SS-OCT [7].

Fig. 4 shows the dynamic tuning range against drive frequency, illustrating a near critically damped fundamental resonance of 340 kHz. Given the relatively flat frequency response (with a fitted mechanical quality factor of 1.3), the usable bandwidth of these devices under sinusoidal sweeping extends beyond 500 kHz. Since SS-OCT can utilise a bidirectional scanning mode, this enables an axial scan rate of >1 MHz, similar to the speeds demonstrated previously in our 1310 nm devices [7].

Conclusion: We have demonstrated the first MEMS-VCSELs in the 1060 nm wavelength range. In addition to the wide accessible wavelength span and high sweep rates, the continuous singlemode tuning nature of these devices enables long dynamic coherence length, translating to long imaging range for use in whole-eye imaging. With this advancement, ultra-widely-tunable MEMS-VCSELs similar to those described here have been incorporated into ophthalmic imaging systems and enable superior images of the human eye at axial scan rates ranging from 50 kHz to >0.5 MHz, which will be described in follow-up publications.

Acknowledgments: This work was supported by the National Cancer Institute grant R44CA101067 and matching funds provided by Thorlabs. The content is solely the responsibility of the authors and does not necessarily represent the views of the National Cancer Institute of the National Institute of Health.

6 September 2012
doi: 10.1049/el.2012.3180
One or more of the Figures in this Letter are available in colour online.

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