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Invited Paper

MEMs-HCG VCSELs for emerging sensing and datacoms applications

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ABSTRACT

We report recent advances in electrically-pumped 1050 nm and 1550 nm micro-electro-mechanically-tunable vertical-cavity surface emitting-lasers (MEMS-VCSELs). We demonstrate a single-mode, continuous, mechanical tuning range of 73 nm with high output power and low threshold current performance for the 1050 nm devices. To the best of our knowledge, 73 nm is a record tuning value for an electrically-pumped tunable VCSEL with a tuning speed >250 kHz, making them highly desirable for next generation OCT and other swept source applications. 10 Gbps 1550-nm DWDM tunable SFP+ modules based on an HCG-VCSEL are demonstrated with an embedded communications channel for automatic wavelength tuning and locking for low cost FTTx and front haul network applications.

Keywords: MEMS, VCSEL, HCG, Wide tuning, High speed, High tuning speed

1. INTRODUCTION

MEMs-tunable lasers are attractive light sources for a wide range of applications such as the optical coherence tomography (OCT) [1], optical communications [2], sensing applications such as gas sensing in hostile environments [3] and, fiber Bragg gratings (FBGs) [4].

Several laser structures have been proposed that reduce the cost and complexity from the conventional sampled grating-based approach to tunable lasers [5], including V-cavity lasers [6] and external cavity polymer reflector-based lasers [7]. A low-cost tunable laser module [8] is a key component for realizing cost-effective swept-source (SS-)OCT and wavelength-division-multiplexed passive-optical-network (WDM-PON) systems.

High-speed SS-OCT is a rapidly emerging ophthalmologic technique with higher resolution than previous OCT techniques [1, 9]. 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 [9], which are considerably more costly, bulky, and complex to fabricate than conventional electrically-pumped VCSELs. The electrically-injected devices are desirable for low-cost compact sources due to the elimination of many components and related assembly like the pump laser, the pump isolator and the multiplexer. The inherent challenges for electrically-pumped devices are the tuning range, which is limited due to the increased cavity losses due to dopants and current spreading considerations, and the single mode operation which is limited by the lateral guiding of the electrical aperture. Electrically-pumped MEMs tunable VCSELs have steadily matured in recent years [1, 10-12] but had not yet been realized with a mechanical tuning range exceeding 70 nm, desired for commercial applications.

The access market has increasing requirements for bandwidth driven by ever increasing data demand from consumers and businesses. Both cellular networks and fiber-to-the-x (FTTx) networks are under the same stresses. Cellular operators have been exploring multiple approaches to deal with this increased demand in the front haul market, increasing the numbers of cells as well as implementing C-RAN-based (cloud radio access network) architectures [13]. A C-RAN-based network architecture pushes the lengths required of front haul networks from a few hundred meters to up to ~15 km kilometres. A low-cost C-RAN implementation may require the use of a PON architecture instead of a point-to-point architecture, which was the dominant fronthaul approach used in the past, depending on installation conditions. A WDM-PON-based architecture is desirable deploying a low-cost system given the low latency and high bandwidth requirements of a C-RAN, especially when an already in place optical fiber is being reused. Besides mobile

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applications, FTTx has similar scenarios where upgrading the bandwidth of an existing installation can be most effectively done using a WDM-PON architecture.

To date, the approaches of other tunable laser structures, reported in [5-8], have not been able to meet the required speeds (10+ Gbps) and/or power requirements (<1.5 W) desirable for front haul applications. Additionally, these new technologies have not been proven to scale to meet the costs desirable for WDM-PON. VCSELs on the other hand are the most widely deployed laser source on the market with high reliability and are the lowest cost point laser available.

Besides the laser chip itself, another key cost driver of a conventional tunable laser-based SFP+ is the integrated wavelength locker, which requires multiple photodetectors, an etalon filter and the related packaging, increasing the cost of the wavelength-tunable TOSA significantly. In order to remove this high cost item, there has been great interest in utilizing an over fiber wavelength tuning and locking mechanism, which can also be used to send DDMI (Digital Diagnostics Monitoring Interface). These systems, commonly referred to as AMCC (auxiliary management and control channel) offer a path to a lower cost tunable transceiver [14-17]. One such system is the ITU-T Recommendation G.698.4 (ex. G. metro). G. metro is designed for externally modulated lasers, which is not applicable to directly modulated lasers. Regardless of whether the laser is externally or directly modulated, the common approach is to use a low frequency (<100 kHz), small modulation depth (5-10%) signal to transfer the data, without interfering with the high-speed data path. These systems can be implemented with small changes to the SFP+ circuitry as is reported in this paper.

We experimentally demonstrate in this paper a wavelength-tunable laser with a single longitudinal-mode cavity that operates mode-hop-free throughout its entire mechanical tuning range, with an acceptable output power and threshold current across the entire tuning range at 1060 nm and at 1550 nm. We package the tunable VCSEL in a TO-can, TOSA and SFP+, making it fully suitable for commercial applications operating from -40º C to +85º C. Here we present the details of the experimental results of our 1060 nm MEMs tunable VCSELs performance emitting at the tuning range center of 1030 nm and show the potential increase to 100+ nm tuning range. In addition, our 1550 nm SFP+ emitting at the tuning range center of 1545 nm are discussed with respect to their wavelength control using AMCC, large signal modulation behaviors and reliability.

2. ELECTRICALLY PUMPED 1050 NM MEMS HCG-VCSELS PERFORMANCE

A key enabling technology in the wavelength-tunable VCSELs presented here is the high-contrast grating (HCG) layer, which is used in place of a top DBR mirror in a conventional VCSEL. The HCG is integrated above an active region and bottom DBR mirror in a GaAs-based material system for our MEMs VCSELs [18], as shown in Fig. 1 left). The HCG is a single layer of high refractive index material, which exhibits high reflectivity across a wide tuning range of 100+ nm. An SEM image of a fabricated HCG is shown in Fig. 1 right). By applying a reverse bias voltage between the p-DBR and suspended HCG, the HCG mirror actuates downwards towards the body of the VCSEL, changing the effective cavity length resulting in different wavelength tuning responses. The whole structure is grown in one single epitaxy growth step 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 [5, 18] and a wide tuning speed. 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 [10], 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 [19-20], with the fabrication process modified so the device can be packaged in a TO-Can and TOSA. 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. 2 left, 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 102 nm tuning range and is under fabrication.

The threshold gain (Gth) of the optimized (blue) design is slightly higher than the current design (red) at the tuning center. The threshold gain remains the same when tuning slightly far away from the bandwidth center while it has lower Gth at the edge of the bandwidth. In the new structure, we have optimized our tunable VCSEL design structure to have a wide single mode continuous tuning range of ~102 nm with high wavelength sweep speed, which allows for even higher resolution OCT target applications.

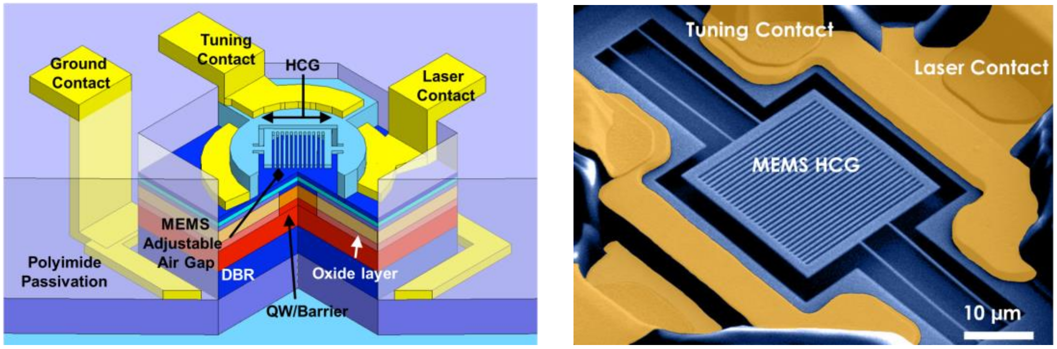

Figure 1. Left) Schematic of our MEMS tunable VCSELs at 1060 nm, and Right) a tilted view SEM image of our fabricated device.

The measured output power and voltage at the TO level versus the current are presented in Fig. 2 right under continuous wave room temperature operation. Typical output power of ~ 2mW at 7mA and a threshold current of 1mA are obtained around the tuning center. The laser diode operating voltage with no tuning is 5 V obtained at 7mA and 25ºC indicating a series resistance of around 250 Ω which is very close to the forward voltage reported in [1]. By increasing the tuning voltage, the laser diode voltage remains constant.

The measured cavity wavelength characteristics of our processed devices as a function of the tuning voltage is shown in Fig. 3 left). The device exhibits strongly single transverse-mode lasing at 4 mA and 25ºC 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 with SMSR above 20 dB. This range corresponds to a $\Delta\lambda/\lambda$ of 6.9%, which is a record for electrically pumped VCSELs. 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, 9-12].

For this device, 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 at the edges of the tuning range, suitable for OCT applications across the entire tuning range.

In addition, we performed the scan rate measurements at 4mA and 25ºC for several different MEMs frequencies. In Fig. 3 right), we present the relative tuning response of our 1050 nm tunable VCSEL at several different frequencies. The full tuning sweep is achievable up to 260KHz with a resonance frequency of 250KHz. The 3dB frequency of the device is 370KHz. 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.

The linewidth of our devices is broad due to the noise induced by the Brownian motion, introduced by the MEMs which vibrates the top mirror as the wavelength is changed by the variation of the top mirror position. The linewidth of our HCG MEMS-VCSELs were measured using a self-heterodyne interferometer with different fiber delay differences. The MEMs-VCSEL device linewidth is extracted to be ~250MHz which is narrow compared to the linewidths reported in [21, 22] using self-heterodyning and heterodyning techniques. This measured linewidth of 250MHz gives a coherence length of ~400 mm in air, making them well suited for OCT applications.

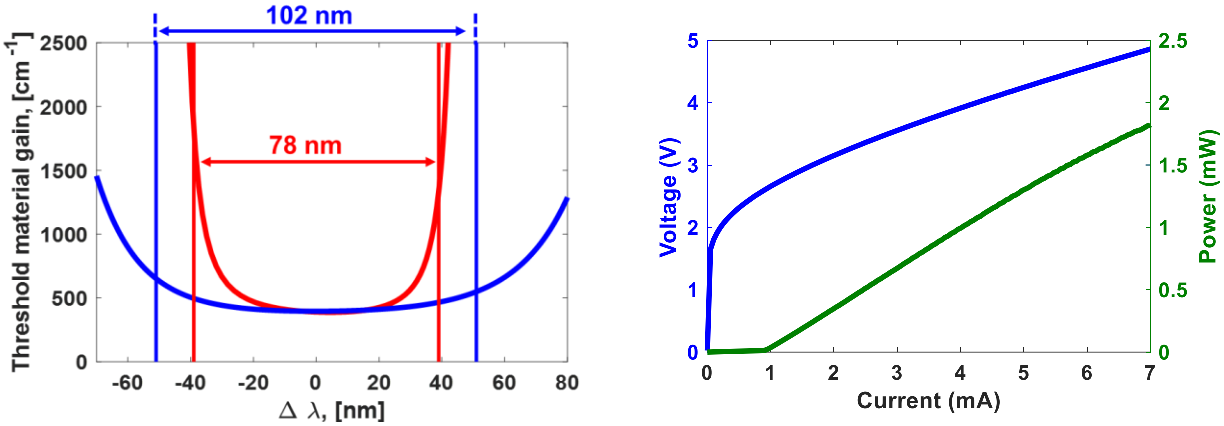

Figure 2. Left) The threshold material gain as function of the tuning wavelength for the investigated VCSEL design (red) and a new optimized design still under fabrication (blue), including intrinsic losses. Right) The LIV characteristics of a 1050 nm MEMs tunable VCSEL device at 25^{o}C at the TO-level under room temperature continuous wave operation.

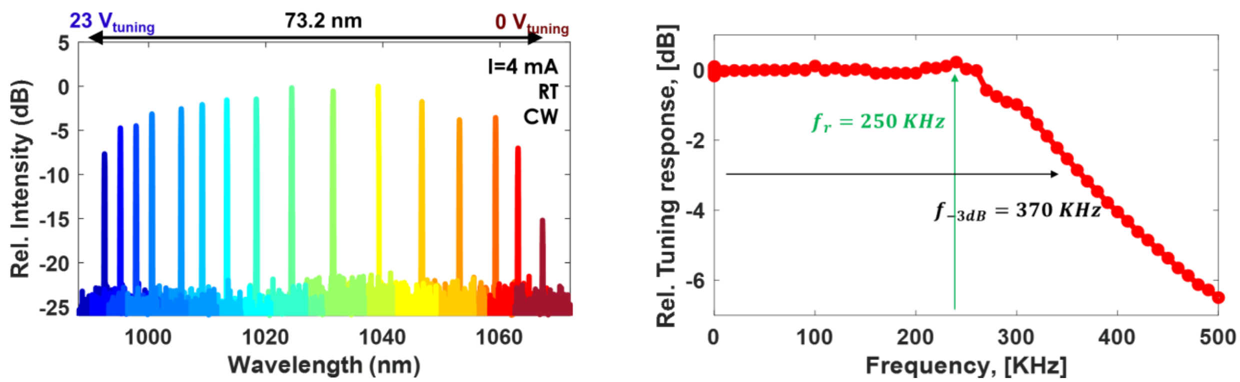

Figure 3. Left) Measured cavity wavelength at 25^{o} C and 4 mA of the MEMs tunable VCSELs for the red design in Fig. 2. Right) The relative tuning response versus the MEMS input frequency of our MEMS tunable device at 25°C and I=4mA. A -3dB frequency of 370 kHz is seen.

3. 1550 MEMS HCG-VCSELS PERFORMANCE

1550 nm MEMS HCG-VCSELs are based on an InP substrate, which makes for several major changes from the GaAs structure used in the 1050 nm MEMS HCG-VCSEL presented above. The most significant difference is the use of a proton implant and a tunnel junction for the InP-based VCSEL versus an oxidation aperture for the GaAs-based VCSELs. The 1550 nm tunable VCSEL uses a similar epitaxial structure to those previously demonstrated [19, 20]. To make the tunable VCSEL structure capable of high-speed direct modulation at 10 Gbps, we designed a structure to have a high-speed ground-signal (GS) contact configuration. Making the VCSELs tunable requires the addition of a single contact, which is used to actuate the structure's MEMS. The contact pads are placed on top of a polyimide passivation layer to reduce parasitic capacitance due to the pads, mesa, and MEMS. The mesa and MEMS were optimized to fit in a much smaller area, reducing the VCSEL's overall capacitance.

Output powers exceeding 2 mW and threshold currents below 7mA are achieved at room temperature and across the full tuning range as shown in Fig. 4 left). Fig. 4 right) shows the tuning range of an optimized tunable HCG VCSEL as a function of applied tuning voltage. The VCSEL is biased at 14 mA under continuous wave room temperature operation, and the tuning voltage is applied between the positive laser contact and the tuning contact, causing the HCG to be pulled downward by electrostatic force. As the tuning voltage was increased from 0 to 14.5 V, a tuning range of ~25 nm can be achieved. Throughout the tuning range, the VCSEL lases in a single mode with a side mode suppression ratio exceeding

40 dB. The tuning range is limited by pull-in of the MEMS and can be further increased by increasing the size of the air gap between the VCSEL body and the HCG.

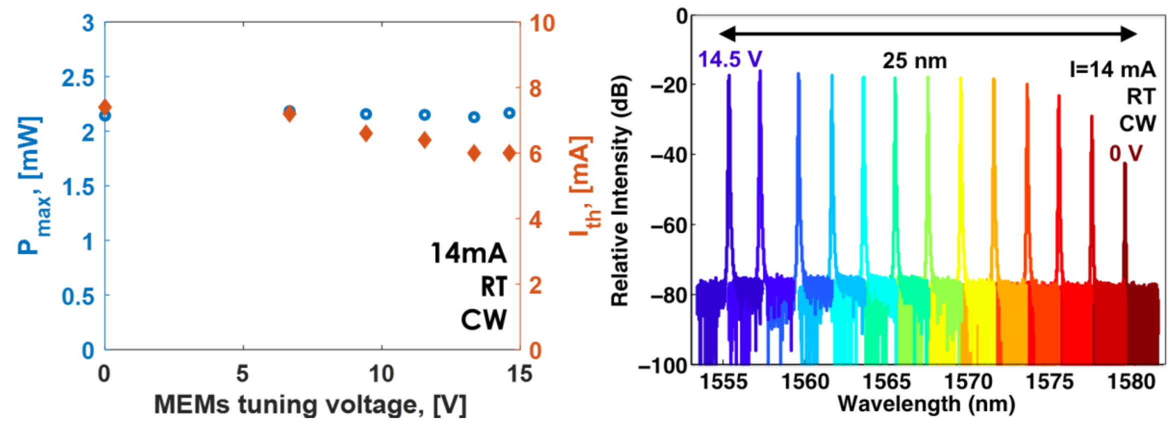

Figure 4. Left) The maximum power output and threshold current as a function of tuning voltage across the MEMS tuning range of a typical device, showing only mild change in performance across the tuning range. Right) The optical spectra of a typical tunable VCSEL with a constant laser bias of 14 mA as a function tuning voltage. As the tuning voltage is increased from 0 V to 14.5 V, the wavelength blue shifts over an ~25 nm wavelength range.

Fixed-wavelength VCSELs have proven to be the key technology enabling commercially successful, high volume, low cost optical transceivers. Wavelength tunable 1550 nm VCSELs [23] have been identified as a strong contender for low cost WDM-PON front haul and FTTx applications [14].

We have shown a low cost tunable VCSEL-based SFP+ with a fully integrated AMCC system [15]. This module is a very cost competitive solution for next generation low-cost WDM-PON-based front haul systems.

3.1 Low-cost Tunable VCSEL SFP+

A tunable SFP+, shown in Fig. 5, has been developed integrating a High Contrast Grating (HCG) tunable VCSEL [24] as its laser source. When integrated in an SFP+ with an APD, the module can be used in systems with link budgets up to ~18 dB in industrial temperature environments. The laser is temperature-stabilized on an integrated TEC inside of the TOSA.

The modules are capable of a 10+ nm tuning range with 10 Gbps performance (equivalent to 12+ channels spaced at 100 GHz) and a SMSR exceeding 50 dB. They have ~+1~-3 dBm output power across their tuning range as shown in Fig. 6 left). Uniform extinction ratios of 5±0.1 dB are also seen across the tuning range of the device at 10 Gbps.

The modules can be used to transmit data at 10 Gbps over 10 km of single mode fiber without any dispersion compensation or forward error correction (FEC). Fig. 6 right) shows BER (bit error rate) as a function of received power for 4 channels spanning the module's tuning range in a back to back configuration and after transmission through 10 km of SMF-28 fiber. An ~2.7 dB power penalty is seen after transmission through 10 km of SMF-28 fiber for all channels. Extension of the link length can be realized through inclusion of a dispersion compensation module (DCM) in the system or alternatively a forward error correction (FEC) or electronic dispersion compensation (EDC) scheme. In a WDM-PON system, a single DCM can be included at the AWG so that the DCM cost is amortized across all channels in the system simultaneously.

Figure 5. SFP+ based on a tunable VCSEL.

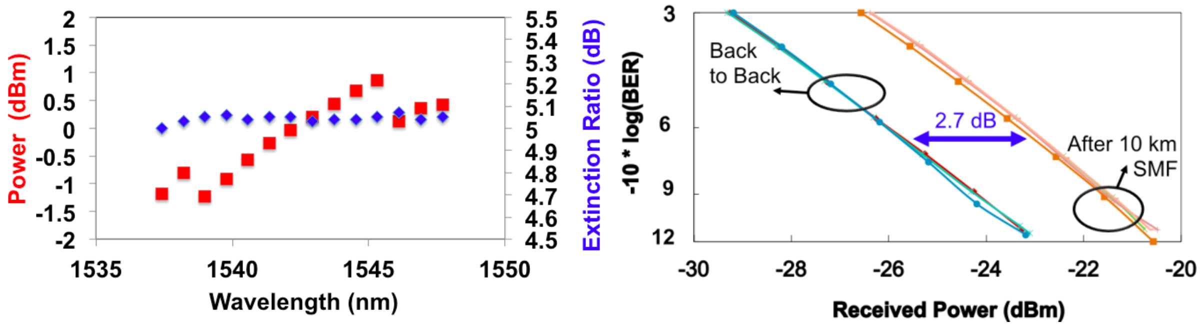

Figure 6. Left) Power and extinction ratio (ER) at 10 Gbps of 14 channels of a tunable SFP+. Uniform ER seen across all 14 channels and power of -0.2±1 dBm. Right) The Bit Error Rate at 10 Gbps as a function of received power for 4 channels across the tuning range of the module back-to-back and after 10 km fiber transmission. A power penalty of ~2.7 dB is seen due to 10 km of fiber.

3.2 Wavelength Control using AMCC

The SFP+ module has integrated AMCC functionality implemented for automatically changing channels and fine-tuning the center wavelength of the device within a given channel as well as sending DDMI information.

The experimental setup of the feedback loop of the system is shown in Fig. 7 left). A control signal is sent from one tunable SFP+ to the other tunable SFP+ as a low amplitude (~10%), low speed signal on top of the high-speed signal over 10 km of SMF-28 and through two AWGs. The MCU (Microcontroller unit) can inject a low speed signal to the transmission path to send commands to the transceiver on the other side of the link. The MCU of the downstream SFP+ receives the signal after low speed filter from the ROSA and decodes the signal, and then responds to the command, either changing channels or tuning within the channel to fine tune the wavelength. This communication scheme works in a bidirectional manner.

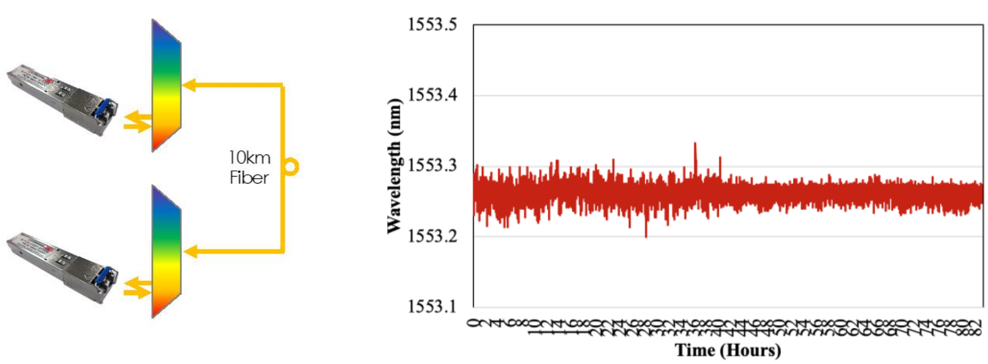

Figure 7. Left) Schematic of a bidirectional wavelength stabilization technique implemented using 2 SFP+s and the AWG's filtering effects to detect the channel center wavelength automatically. Right) The laser's center wavelength as a function of time with the AMCC-based wavelength stabilization technique enabled. On average, a wavelength drift of <1 GHz is seen in this measurement limited setup over 80 hours.

The SFP+ monitors the power received at its ROSA from the peer tunable SFP+ after it passes through the AWG. In the case of changing channels, the signal may disappear entirely and go to another SFP+ in the system. For wavelength fine-tuning, the signal is seen as a slight change in the received power due to filtering from the AWG. After finding and characterizing this change in power to characterize the filter being used in the setup, the SFP+ sends another command to its peer as needed to set the wavelength to the filter center. Fig. 7 right) shows the center wavelength of the laser versus time with the AMCC-based wavelength stabilization system running. A wavelength change of < 1 GHz is obtained on average in the measurement limited system over 80 hours, showing the system can keep the wavelength stable with a high degree of precision.

3.3 1550 nm VCSEL Reliability

While these continuously MEMS-tunable 1550nm VCSELs, in a TOSA package, have passed all the usual reliability tests required by Telcordia GR468, the long-term accelerated aging tests of the HCG-VCSEL chip, in a simple TO-56 can, are still in progress. A summary of the test results so far is presented below.

In the first batch, we had 155 parts, (approximately evenly split between 3 different lots of chips), operating inside an oven held at 85ºC, with each VCSEL being stressed at a constant bias current of 15 mA, with no tuning voltage applied. Using the measured thermal resistance of 1.9 K/mW, we estimate the junction temperature during stress to be about 123ºC, which is about 45ºC hotter than the junction temperature of 78ºC under typical operating conditions. This implies, for an activation energy of 0.7eV, an acceleration factor of only 13.8.

The parts are taken out of the oven roughly once a week and tested at room temperature using a swept current source to measure both optical power and forward voltage over its operating range.

As Fig. 8 shows, no failures have been observed with the output power at 15mA being fairly constant, within expected small variations in room temperature, for about 6800 hours and counting. For the actual 1.1 million device-hours so far with zero failures, we can thus predict a failure in time (FIT, in failures per 1 billion hours) of <149 with 90% confidence, and a FIT of <59 with 60% confidence level.

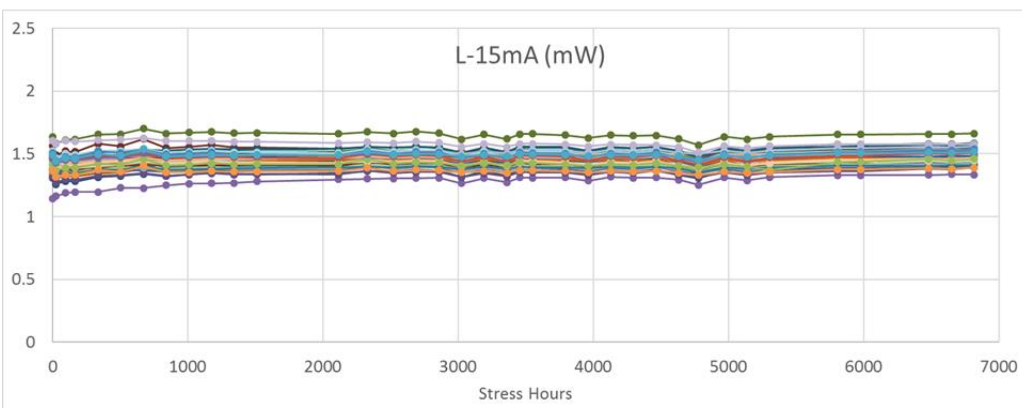

Figure 8. Output power at 15mA versus time spent at biased 85º C operating conditions

In another batch, we had 60 parts, evenly split between 3 different lots, operating inside an oven held at 85ºC, with each VCSEL being stressed at a constant bias current of 20 mA, and with 15V tuning applied. In this case, we estimate the junction temperature during stress to be about 142ºC, which is about 64ºC hotter than the junction temperature of 78ºC under typical operating conditions. This implies an acceleration factor of 35.6, for the assumed activation energy of 0.7eV. These parts were also taken out roughly once a week and tested at room temperature.

Again, no failures have been observed, with the output power being fairly constant, at a constant 15mA current bias and 15 V tuning bias, for about 4800 hours and counting. For the actual 288 thousand device-hours with zero failures, we can thus predict a FIT of <224 with 90% confidence, and a FIT of <89 with 60% confidence level, for this batch separately. Of course, combining the two batches, we predict even lower failure rates.

4. CONCLUSION

In summary, we present high performance, widely and continuously tunable, electrically-pumped VCSELs at 1060 nm wavelength center with low DC bias voltage. The laser is single mode at all tuning voltages across the full tuning range and can be mechanically actuated at frequencies up to ~370 KHz (the -3dB point). A coherence length of ~400 mm is achieved, which is suitable for next generation swept source OCT applications. In addition, a wavelength tunable VCSEL-based SFP+ module has been demonstrated with integrated AMCC wavelength stabilization protocol. The VCSEL chips themselves are found to be highly reliable with FITs <60 after over 1 million cumulative device hours. The AMCC protocol is able to keep the laser center wavelength within ±1 GHz of the center of an AWG filter channel. The tunable SFP+ modules operate over a 14+ nm tuning range at 10 Gbps and, are a competitive solution for next generation front haul access networks utilizing WDM-PON. HCG-based tunable VCSELs are a prime candidate for enabling low cost applications using tunable lasers.

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REFERENCES

[1] D. John, C. B. Burgner, B. Potsaid, M. E. Robertson, B. K. Lee, W. J. Choi, A. E. Cable, J. G. Fujimoto, and V. Jayaraman, “Wideband electrically-pumped 1050 nm MEMS-Tunable VCSEL for ophthalmic Imaging,” IEEE J. Light. Tech., 33(16), 3461 - 3468, (2015).

[2] C. Gierl, K. Zogal, S. Jatta, H. A. Davani, F. Küppers, P. Meissner, T. Gründl, C. Grasse, M.-C. Amann, A. Daly, B. Corbett, B., Kögel, A. Haglund, J. Gustavsson, P. Westbergh, A. Larsson, P. Debernardi, and M. Ortsiefer, “Tunable VCSEL aiming for the application in interconnects and short haul systems”, SPIE Optical Metro Networks and Short-Haul Systems III, 7959(1), 795908, (2011).

[3] T. Bond, G. Cole, L. Goddard and E. Behymer, “Photonic MEMS for NIR in-situ gas detection and identification,” 6th IEEE Conference on SENSORS, 1368–1371, (2007).

[4] T. Mizunami, S. Hirose, T. Yoshinaga and K. I. Yamamoto, “Power-stabilized tunable narrow-band source using a VCSEL and an EDFA for FBG sensor interrogation”, Measurement Science and Technology, 24(4), (2013).

[5] K. Grobe, M. H. Eiselt, S. Pachnicke, and J.-P. Elbers, “Access Networks Based on Tunable Lasers,” J. Light. Technol., 32(16), 2815–2823, (2014).

[6] Y. A. Akulova et al., “Widely tunable electro absorption-modulated sampled-grating DBR laser transmitter,” IEEE J. Sel. Top. Quantum Electron., 8(6), 1349–1357, (2002).

[7] J. Meng, H. Zhu, S. Zhang, L. Zou, and J.-J. He, “Direct Modulation of Widely Tunable V-Cavity-Laser for Low-Cost WDM Access Networks”, Asia Communications and Photonics Conference, (2013).

[8] S. Hwan Oh, K.-H. Yoon, K. S. Kim, J. Kim, O.-K. Kwon, D. K. Oh, Y.-O. Noh, H. Lee, “Tunable External Cavity Laser by Hybrid Integration of a Superluminescent Diode and a Polymer Bragg Reflector,” IEEE J. Sel. Top. Quantum Electron., 17(6), 1534–1541, (2011).

[9] V. Jayaraman, D.D. John, C. Burgnera, M.E. Robertson, B. Potsaid, J.Y. Jiang, T.H. Tsai, W. Choi, C.D. Lu, P.J.S. Heim, J.G. Fujimoto, and A.E. Cable, “Recent advances in MEMS-VCSELs for high performance structural and functional SS-OCT imaging,” Proc. SPIE 893402-1, (2014).

[10] P. Qiao, K. T. Cook, K. Li and C. J. Chang-Hasnain, “Wavelength Swept VCSELs,” IEEE J. Sel. Topics. Quantum Electron., 23(6), May (2017).

[11] K. Li, C. Chase, P. Qiao, and C. J. Chang-Hasnain, “Widely tunable 1060-nm VCSEL with high contrast grating mirror,” Optics Express, 25(10), 11844-11854, (2017).
[12] V. Jayaraman, G.D. Cole, M. Robertson, C. Burgner, D. John, A. Uddin, and A. Cable, “Rapidly swept, ultra-widely-tunable 1060 nm MEMS-VCSELs,” Electron. Lett., 48(21), 1331, (2012).
[13] T. Pfeiffer, “Next Generation Mobile Fronthaul and Midhaul Architectures”, J. Opt. Commun. Netw., 7 (11), B38, (2015).
[14] C. W Wagner, J. Zou, M. Ortsiefer ; C. Greus ; C. Neumeyr ; K. Grobe, “Full C-band Tunable MEMS-VCSEL for Next Generation G. metro Mobile Front-and Backhauling,” IEEE Optical Fiber Communication Conference, W2A–27, (2017).
[15] H. K. Chen, C. Chase, and M. Huang, “10 Gbps Tunable VCSEL-based SFP+ with Integrated G.METRO Functionality for Front haul Access Networks,” European Conference on Optical Communication, (2017).
[16] C. Wagner et M. Eiselt, S. Zou, M. Lawin, B. Teipen, K. Grobe, J.J. Vegas Olmos, I. T. Monroy, “Wavelength-agnostic WDM-PON system” 18th International Conference on Transparent Optical Networks, 1–4, (2016).
[17] F. Cavaliere, L. Giorgi, and L. Poti, “Transmission and Switching Technologies for 5G Transport Networks,” IEEE Optical Interconnects Conference, (2018).
[18] D. Ellafi, M. Yang, S. Kim, N. Bandyopadhyay, C. Chase, ”Electrically-Pumped 1050-nm MEMs Tunable VCSELs Wide tuning Range for OCT Applications”, IEEE International Semiconductor Laser Conference, 99-100, (2018).
[19] C. Chase, Y. Rao, W. Hofmann, and C. J. Chang-Hasnain, “1550 nm high contrast grating VCSEL,” Opt. Express, 18(15), 15461–15466, (2010).
[20] Y. Rao, W. Yang, C. Chase, M. C. Y. Huang, D. P. Worland, S. Khaleghi , M. R. Chitgarha, M. Ziyadi, A. E. Willner, C. J. Chang-Hasnain, “Long-Wavelength VCSEL Using High-Contrast Grating” IEEE J. Sel. Top. Quantum Electron., 19(4), 1701311–1701311, (2013).
[21] H. Halbritter, C. Sydlo, B. Kogel, F. Riemenschneider, H. L. Hartnagel and P. Meissner, "Impact of micromechanics on the linewidth and chirp performance of MEMS-VCSELs," IEEE J. Sel. Top. Quantum Electron., 13(2), 367-373, (2007).
[22] D. Huber, P. Corredoura, S. Lester, V. Robbins and L. Kamas, "Reducing Brownian motion in electrostatically tunable MEMS laser," J. of Microelectromech. Syst., 13(5), 732-736, (2004).
[23] J. Boucart, R. Pathak, D. Zhang, M. Beaudoin, P. Kner, D. Sun, R.J. Stone, R.F. Nabiev, W. Yuen, “Long wavelength MEMS tunable VCSEL with InP-InAlGaAs bottom DBR,” IEEE Photonics Technol. Lett., 15(9), 1186–1188, (2003).
[24] C. Chase, Y. Rao, M. Huang, and C. Chang-Hasnain, “Tunable 1550nm VCSELs using high-contrast grating for next-generation networks,” Proc. SPIE 9008, 900807, (2014).