WAVELENGTH ENGINEERING OF SURFACE EMITTING LASERS FOR HIGH CAPACITY SHORT REACH SYSTEMS

Fumio KOYAMA

Microsystem Research Center, Tokyo Institute of Technology,
4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan
TEL: +81-45-924-5068, FAX: +81-45-924-5961, EMAIL: koyama@pi.titech.ac.jp

ABSTRACT

In this paper, we present the wavelength engineering of surface emitting lasers for use in high speed short reach systems, which may include the wavelength expansion, the wavelength integration and the wavelength stabilization based on fully monolithic VCSEL technologies. We have developed highly strained GaInAs/GaAs QW VCSELs emitting at 1.1-1.2 μm band and GaInNAs/GaAs VCSELs at 1.3 μm wavelength. Excellent temperature characteristics have been realized. We extended the emission wavelength of highly strained GaInAs QWs up to 1.2 μm and demonstrated low threshold operations of 1.3 mm GaInNAs lasers grown by MOCVD.

We carried out the growth of highly strained GaInAs/GaAs quantum wells on a patterned substrate for realizing multiple wavelength VCSEL arrays in a wide wavelength span. We demonstrated a single-mode multiple-wavelength VCSEL array on a patterned GaAs substrate covering a new wavelength window of 1.1- 1.2 μm. By optimizing a pattern shape, we achieved multiple-wavelength operation with widely and precisely controlled lasing wavelengths. The maximum lasing span is over 190 nm.

We proposed and demonstrated a micromachined tunable vertical cavity with a stress control layer, which gives us novel functions including temperature insensitive operation, thermal wavelength tuning, and so on. Either temperature insensitive operation or wide wavelength tuning induced by temperature change can be realized. The temperature insensitive VCSEL based on this technology may be helpful for decreasing the channel spacing in coarse WDM systems.

We demonstrated long wavelength GaInAs and GaInNAs VCSELs on GaAs substrates, enabling uncooled operation for high speed data transmission in single-mode fibers. The multiple-wavelength array and wavelength engineering of VCSELs may open up ultra-high capacity short reach systems.

Keywords: tunable filter, tunable laser, MEMS, WDM, wavelength tuning, surface emitting laser

Active and Passive Optical Components for WDM Communications III, Achyut K. Dutta,
Abdul Ahad S. Awwal, Niloy K. Dutta, Kazuo Fujiura, Proceedings of SPIE Vol. 5246 (2003)

1. INTRODUCTION

High speed photonic networks have been extensively developed for long-haul backbone networks. Also, the metro or laocal area networks have seen significantly great capacity demand. Optical interconnections between network equipments are also becoming very important. For these short reach applications, important issues for light sources are small size and low cost . Professor Emeritus K. Iga of Tokyo Institute of Technology invented a vertical cavity surface emitting laser 25 year years ago. A lot of unique features are can be expected, low power consumption, a wafer level testing and so on. Especially, people expect VCSEL technologies for cost effective solutions.

Fast Ethernet and gigapit Ethernets are currently major markets for VCSELs Also, 10G Ethernets are ready now. 850nm VCSELs and 1300 nm VCSEls are candidates for next generation high speed transceivers. The market of vertical cavity surface emitting lasers (VCSELs) is growing up rapidly and they are now key devices in local area networks based on multi-mode optical fibers. Also, long wavelength VCSELs are currently attracting much interest for use in single-mode fiber metropolitan area and wide area networks [1]. Low cost and high performance VCSELs emitting at 1.3 μm may drive significant cost reduction in high speed links of over several km with single mode fibers. We have spent much effort to develop long wavelength VCSELs. Various materials have been studied for long wavelength VCSELs on GaAs substrates, such as GaInNAs/GaAs [2-4], highly strained GaInAs/GaAs [5-7], GaSbAs/GaAs [8] and GaInAs quantum dots [9].

We have developed highly strained GaInAs/GaAs QW VCSELs emitting at 1.1-1.2 μm band and GaInNAs/GaAs VCSELs at 1.3 μm wavelength. Low threshold and excellent temperature characteristics were realized. Also, the wavelength engineering on VCSELs may give us multiple-wavelength sources and tunable devices.

In this paper, we present the wavelength extension of GaIn(N)As VCSELs on GaAs substrate for high speed single-mode fiber data transmission. For future upgrading bit rates toward Tera bps ranges, we will describe multiple-wavelength VCSEL arrays. In addition, we will present some results on MEMS-based vertical cavities for wavelength stabilization as well as for wavelength tuning.

2. WAVELENGTH EXTENSION OF VCSELS ON GaAs SUBSTRATE

The schematic structure of long wavelength VCSELs on a GaAs substrate is shown in Fig. 1. We realized the wavelength extension of GaInAs/GaAs strained quantum wells to open up a new wavelength band of 1.0-1.2 μm[5-7]. We introduced a strained buffer layer and established growth conditions in MOCVD, enabling us to grow highly strained layers with a strain of over 3%. The PL wavelength of grown GaInAa QWs could be extended over 1.2 μm without any degradation in crystal qualities. We are able to expect good temperature performances for GaInAs and GaInNAs QWs due to their strong electron confinement as shown in Fig. 2.

We fabricated highly strained GaInAs VCSELs either on (100) or (311)B GaAs substrates. We achieved a low threshold current of below 1 mA, high-temperature operation of up to 450K, and high reliability of >2000 hours [7]. This device was grown on a GaAs (311)B substrate, showing large orthogonal polarization suppression ratio of 30 dB. We realized single longitudinal, fundamental transverse-mode and polarization operations. The threshold and slope efficiency are almost unchanged up to 80 degree as shown in Fig. 3. A characteristic temperature T_0 is over 200 K, which is much higher than 1.3 μm InP based lasers. The excellent temperature characteristic is due to the deep potential well of this material system.

The extension of the emission wavelength up to 1.2 μm enables high speed data transmission in single mode fibers. We carried out single-mode fiber data transmission experiments using our GaInAs VCSELs. We found that the negative dispersion of a fiber is helpful for short pulse transmission with the frequency chirp of a VCSEL as shown in Fig. 4 [10]. Figure 5 shows the bit error rate and eye pattern under 10 Gbps transmission through a 5 km long single mode fiber [11, 12]. The result shows a potential of highly strained GaInAs VCSELs for use in high capacity networks beyond 10 Gbps.

For further extension of emission wavelength, we have spent effort for realizing GaInNAs/GaAs quantum well VCSELs. Pioneering work on GaInNAs lasers was achieved by Kondow and his co-workers of Hitach. The lasing wavelength could be increased to 1.3 mm or even longer by adding nitrogen of 1% in GaInAs. GaInNAs VCSELs have been demonstrated by using either MOCVD or MBE. Sub-mA low threshold and high temperature operations have been demonstrated. Also, 10 Gbps data transmission experiments were also reported. The threshold current density of MOCVD grown GaInNAs lasers has been reduced below 400 A/cm^2 as shown in Fig. 6 [14]. Figure 7 shows the progress on the threshold current of GaInNAs lasers [15]. We believe 1.3 μm GaInNAs VCSELs would be in production stage soon.

3. MULTIPLE-WAVELENGTH VCSEL ARRAY ON PATTERNED SUBSTRATE

For upgrading bit rates beyond several tens Gbps, we may expect the use of WDM links even for short reach systems. For this purpose, a multiple-wavelength VCSEL array will be a key device. [15] We have spent much effort for realizing multiple-wavelength VCSEL array on patterned substrates [16]. We demonstrated a single-mode multiple-wavelength VCSEL array on a patterned GaAs substrate covering a wavelength window of 1.1- 1.2 μm as shown in Fig. 8 [11,12]. By optimizing a pattern shape, we achieved multiple-wavelength operation with widely and precisely controlled lasing wavelengths. The maximum lasing span reaches 190 nm as shown in Fig. 9 [17]. We carried out data transmission experiment with a 5 km long conventional single mode fiber by using the VCSEL array. Data transmission experiments with 2.5 Gb/s x 4 channels were achieved. We also demonstrated a densely integrated multi-wavelength

VCSEL array with a spacing of 50 μm as shown in Fig. 10 [18]. The wavelength spacing is as small as 0.7 nm as shown in Fig. 11 [18]. In addtion, MEMS technologies [19-21] give us new functions for the wavelength engineering of VCSELs, which may include wavelength tuning and wavelength locking [22].

4. WAVELENGTH CONTROL WITH MICROMACHINED STRUCTURE

Figure 12 shows the basic concept of our proposed micromachined filter. We can freely control the temperature dependence of the proposed MEMS cavity. Either temperature insensitive operation or wide wavelength tuning induced by temperature change can be realized. The temperature insensitive VCSEL based on this technology may be helpful for decreasing the channel spacing in coarse WDM systems. The upper GaAlAs/GaAs distributed Bragg reflector (DBR) is freely suspended above the substrate. An air gap is formed between the upper and bottom GaAlAs/GaAs DBRs. In the micromachined filter, when a voltage is applied at the air gap, the electrostatic attraction causes a bending of the cantilever toward the substrate side, which enables wide wavelength tuning. Our structure is similar to that developed for tunable wavelength VCSELs with a micromachined cantilever [21, 23]. A difference in our device is to include an additional thermal stress control layer on the upper DBR with a smaller or larger thermal expansion coefficient than the average expansion coefficient of the GaAlAs/GaAs DBR. The mechanical displacement of the cantilever is caused by the thermal stress, which enables us to control the temperature dependence of the resonant wavelength of the micromachined vertical cavity. We are able to realize either a temperature insensitive operation or wavelength tuning [24, 25]. The temperature dependence can be controlled by some structural parameters, which is the arm length, the difference in thermal expansion coefficient, and the thickness of the thermal stress control layer.

We fabricated two kinds of micromachined vertical cavities either for temperature insensitive operation or for thermal wavelength tuning. Figure 13 shows the SEM view of a fabricated MEMS cavity. We measured the temperature dependence of the resonant wavelength of fabricated cavities [24]. Figure 14 shows the measured reflection spectra of the two different filters for various temperatures. We could obtain either large wavelength tuning or temperature insensitive operation, depending on the stress control layer [24, 25]. We obtained temperature insensitive operation with a small temperature dependence of 0.01nm/K for the 30 nm thick stress control layer. Our results show a possibility of wide wavelength tuning by using a thermal strain-induced displacement of a cantilever structure. We fabricated a light emitting diode having a temperature insensitive resonant cavity as shown in Fig. 15 [26], The measured emission spectra in a temperature range of 20-120 degree C are shown in Fig. 16 [26]. The temperature dependence is as small as 0.013 nm/K, which is 7 times smaller than that of a single-mode laser as shown in Fig. 17 [26]. This result shows a possibility of temperature insensitive VCSELs with wavelength locking. We are able to reduce the channel spacing of multiple wavelength VCSEL array without a temperature controller for course WDM applications.

5. CONCLUSION

We developed long wavelength GaInAs and GaInNAs VCSELs on GaAs substrates, enabling uncooled operation for high speed data transmission even in single-mode fibers. Excellent temperature characteristics have been realized. The growth and device performances of long wavelength VCSELs were presented.

We demonstrated a single-mode multiple-wavelength VCSEL array on a patterned GaAs substrate covering a new wavelength window of 1.1- 1.2 μm. By optimizing a pattern shape, we achieved multiple-wavelength operation with widely and precisely controlled lasing wavelengths. The maximum lasing span is over 190 nm. Also, we carried out a data transmission experiment through a single mode fiber using a multiple-wavelength VCSEL array.

We introduced new functions in micromachiened vertical cavities. We realized a temperature insensitive vertical cavity. The wavelength engineering of VCSELs may open up ultra-high capacity LANs.

ACKNOWLEDGEMENT

The author would like to acknowledge Professor Emeritus K. Iga of Tokyo Institute of Technology for his encouragement. The author would like to thank Prof. T. Miyamoto and laboratory members for their contributions in this study. This work was supported by Grant-in-Aid for Creative Scientific Research from the Ministry of Education, Science, Sport and Culture (#14GS0212”).

REFERENCES

1. K. Iga, IEEE J. Select. Top. Quantum Electron., vol. 6, no. 6, (2000) pp. 1201-1215.
2. M. Kondow, K. Uomi, A. Niwa, T. Kitatani, S. Watahiki and Y. Yazawa, Jpn J. Appl. Phys., 35, pp. 1273-1275, 1996.
3. T. Miyamoto, K. Takeuchi, T. Kageyama, F. Koyama and K. Iga, Jpn. J. Appl. Phys., 37, pp.90-91, 1998.
4. K.D. Choquette, J.F. Klem, A.J. Fischer, O. Blum, A.A. Allerman, I.J. Fritz, S.R. Kurtz, W.G. Breiland, R. Sieg, K.M. Geib, J.W. Scott and R.L. Naone, Electronics Letters , vol.36 , 1388 –1390, 2000.
5. D. Schlemker, T. Miyamoto, Z. Chen, F. Koyama and K. Iga, IEEE Photon. Technol. Lett., 11, 8, 946 948, 1999.
6. F. Koyama, D. Schlenker, T. Miyamoto, Z. Chen, A. Matsutani, T. Sakaguchi, and K. Iga : Electron. Lett., vol. 35, no. 13, 1079, 1999.
7. N. Nishiyama, M. Arai, S. Shinada, T. Miyamoto, F. Koyama, and K. Iga: IEEE J. Select. Top. Quantum Electron., vol. 7, no. 2, 242, 2001.
8. T. Anan, K. Nishi, S. Sugou, M. Yamada, K. Tokutome and A. Gomyo, Electron. Lett., 34, pp.2127-2129, 1998.

9. D.L. Huffaker, H. Deng and D.G. Deppe, IEEE Photon. Technol. Lett., 10, pp.185-187, 1998.

10. T. Kondo, M. Arai, M. Azuchi, T. Uchida, A. Matsutani, T. Miyamoto, and F. Koyama, Electron. Lett., vol. 38, no. 16, (Aug. 2002) pp. 901-903.

11. M. Arai, T. Kondo, M. Azuchi, T. Uchida, A. Matsutani, T. Miyamoto and F. Koyama, IPRM 2002, A3-3, Stockholm, 2002.

12. M. Arai, T. Kondo, A. Matsutani, T. Miyamoto, and F. Koyama, IEEE J. Select. Top. Quantum Electron., vol. 8, no. 4, (Jul. 2002) pp. 811-816.

13. M. Kawaguchi, T. Miyamoto, E. Gouardes, D. Schlenker, T. Kondo, F. Koyama and K. Iga: Jpn. J. Appl. Phys. 40, L744-L746 , 2001.

14. T. Miyamoto and F. Koyama, 7th Optoelectronics and Communication Conf. (OECC2002), Yokohama, Japan, paper 10C2-4, (July 2002) pp. 150-15.

15. C.J. Chang-Hasnain, J.P. Harbison, C.E. Zah, M.W. Maeda, L.T. Florez, N.G. Stoffel and T.P. Lee, IEEE JQE., vol.27, pp.1368-1376, 1991.

16. F. Koyama, T. Mukaihara, Y. Hayashi, N. Ohnoki, N. Hatori and K. Iga, IEEE Photon. Tech. Lett., vol.7, no.1, pp.10-12, 1995.

17. M. Arai, T. Kondo, A. Matsutani, T. Miyamoto and F. Koyama, Device Research Conference 2003,

18. A.Onomura, M. Arai, T. Kondo, A. Matsutani, T. Miyamoto and F. Koyama, Jpn. J. Appl. Phys., vol.42, no.5B, pp.L529-L531, May 2003.

19. M. C. Larson, B. Pezeshki, and J. S. Harris. Jr, "Vertical Coupled-Cavity Micro interferometer on GaAs with Deformable Membarance Top Mirror" *IEEE Photonics Technol. Lett.*, 1995, **7**, pp. 382-384

20. M. S. Wu, E. C. Vail, G. S. Li, W. Yuen, and C. J. Chang-Hasnain, "GaAs micromachined widely tunable Fabry-Perot filter" *Electron. Lett.*, 1995, **31**, pp. 1671-1672

21. C. Chang-Hasnain "Widely tunable VCSEL using MEMS technology", *LEOS 2000*, MF1, 2000, pp. 54-55

22. F. Koyama and K. Iga, OSA Quantum Optoelectronics, QTh-14, pp. 90-92, 1997.

23. T. Amano, F. Koyama, N. Furukawa, N. Nishiyama, A. Mastutani and K. Iga, *Electron. Lett*., vol. 36, 2000, pp. 74-76

24. T. Amano, F. Koyama, N. Nishiyama, and K. Iga, *IEEE Photon. Technol. Lett.*, vol. 12, 2000, pp. 510-512

25. T. Amano, F. Koyama, T. Hino, M. Arai and A. Mastutani, *Journal of Lightwave Technology,* vol. 21, no.3, pp.59-64, 2003.

26. T. Amano, M. Arai, A. Matsutani, F. Koyama, The 50th Spring Meeting of Japan Society of Applied Physics and Related Societies, 2003.

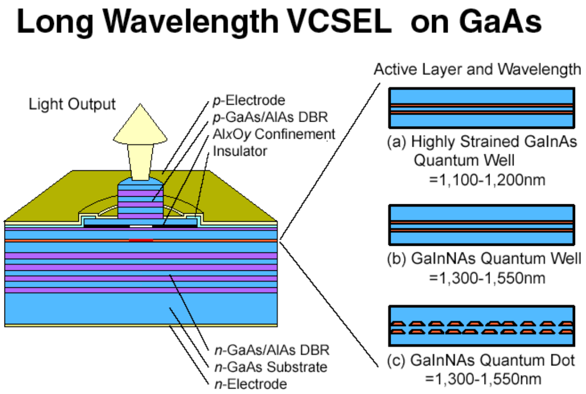


Fig. 1 Schematic structure of long wavelength VCSELs on a GaAs substrate. [14]

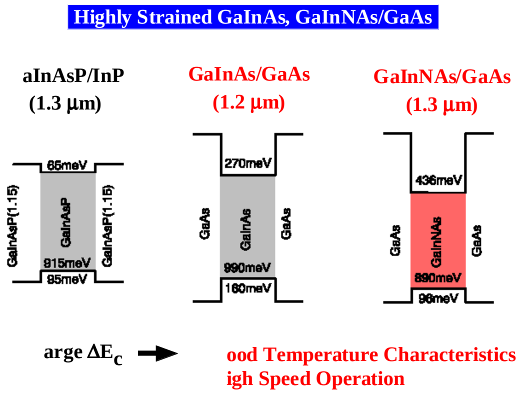


Fig. 2 Band diagram of GaInAs and GaInNAs QWs.

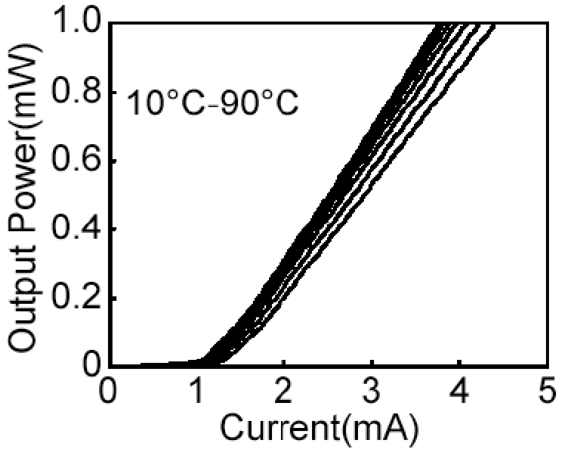
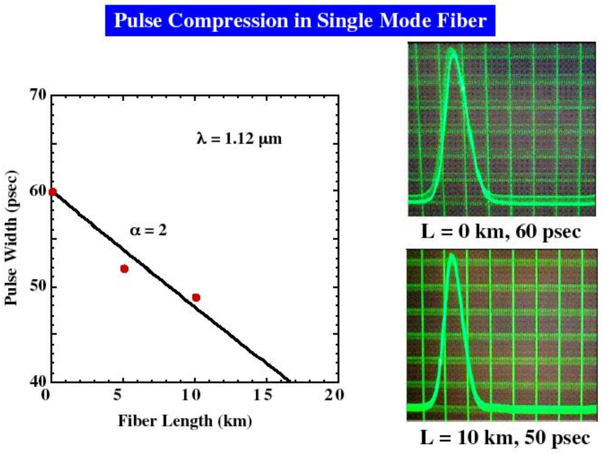


Fig. 3 Temperature dependence of 1.1-1.2 μm GaInAs VCSELs. [7]



Kondo, Arai, Azuchi, Miyamoto, Koyama, OECC 2002

Fig. 4 Pulse compression in 1.2 μm SMF transmission. [10]

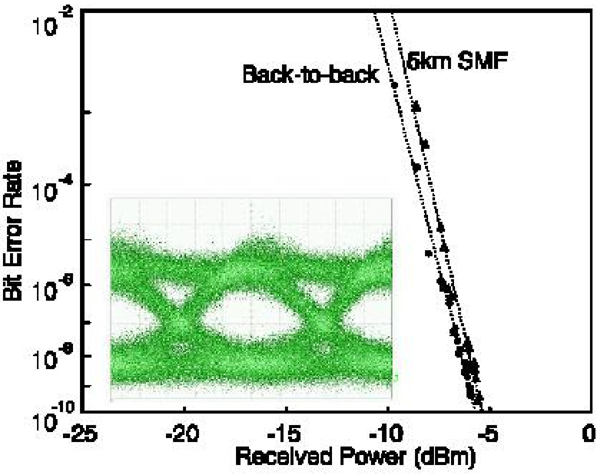


Fig. 5 10Gb/t data transmission using 1.2 μm VCSEL. [11]

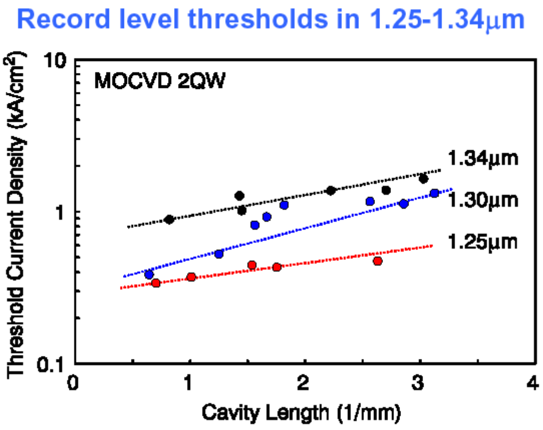


Fig. 6 Low threshold GaInNAs lasers grown by MOCVD. [13]

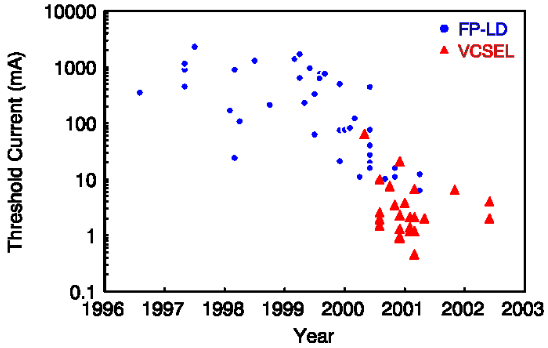


Fig. 7 Progress on threshold of GaInNAs lasers. [14]

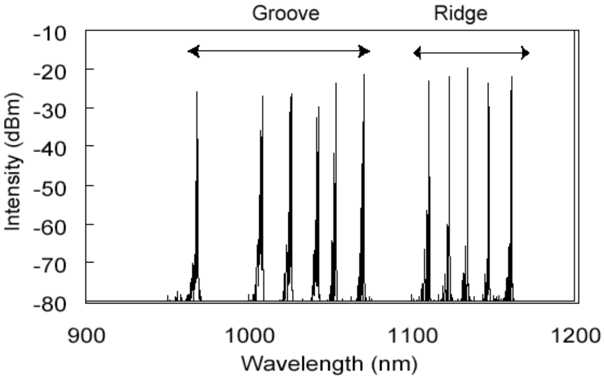


Fig. 9 Lasing spectra of multiple wavelength VCSEL array on patterned substrate.[17]

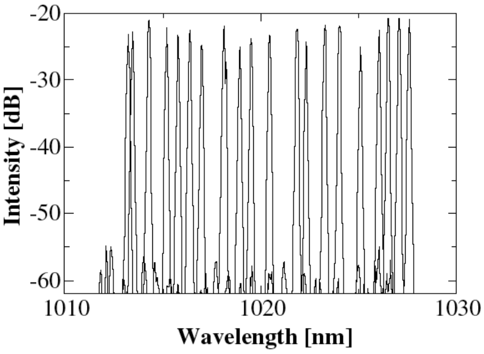


Fig. 11 Lasing spectra of multi-wavelength VCSEL array. [18]

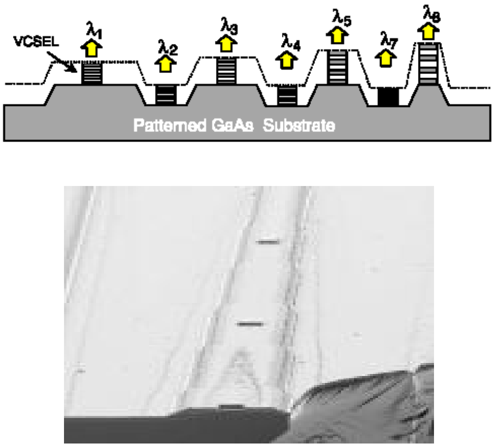


Fig. 8 Schematic of multiple wavelength VCSEL array on patterned substrate.[17]

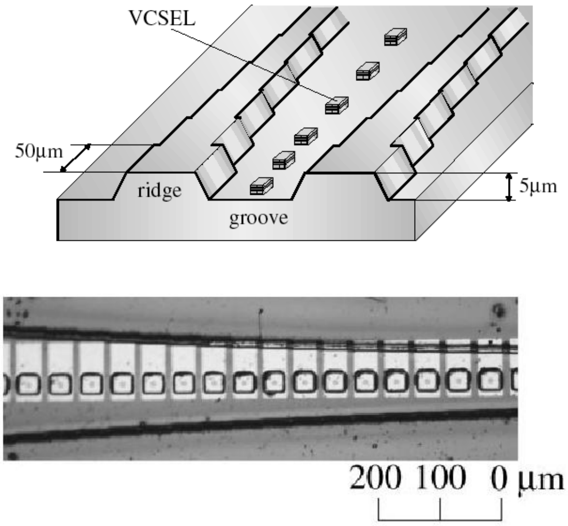


Fig. 10 Densely integrated multi-wavelength VCSEL array. [18]

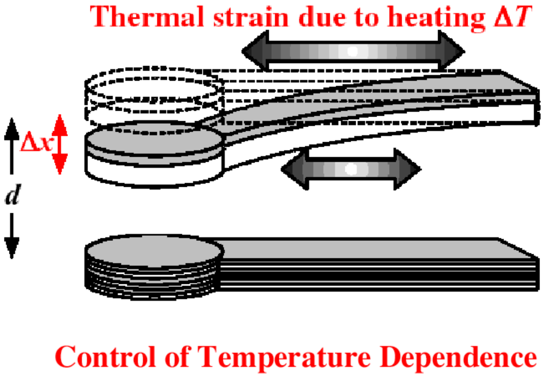


Fig. 12 Wavelength control using MEMS. [22]

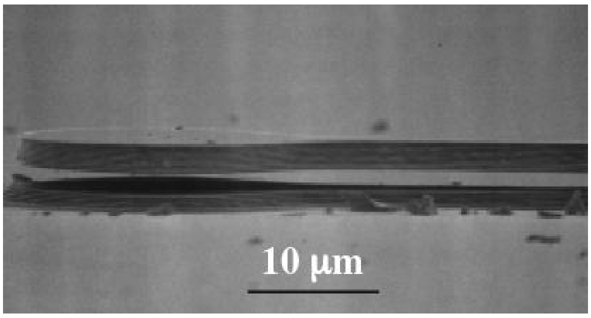


Fig. 13 Fabricated MEMS vertical cavity with a stress control layer. [23]

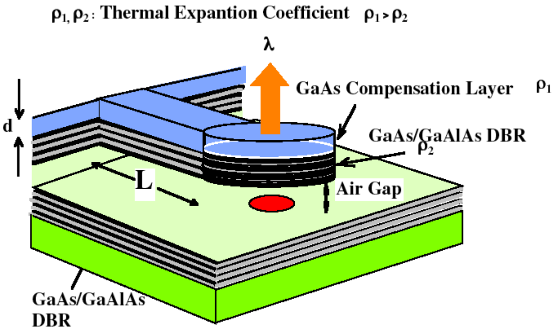


Fig. 15 Light emitting diode with a temperature insensitive vertical cavity. [26]

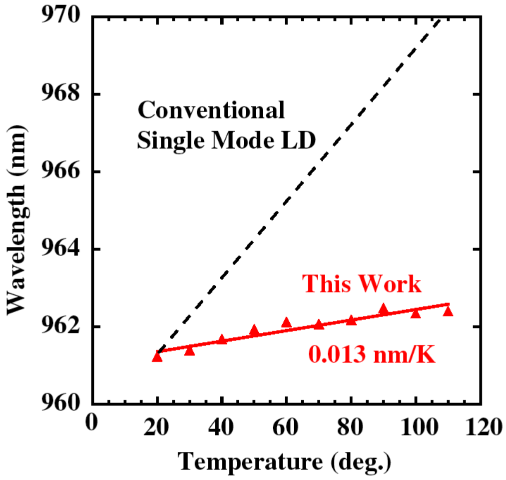


Fig. 17 Temperature dependence of wavelength.[26]

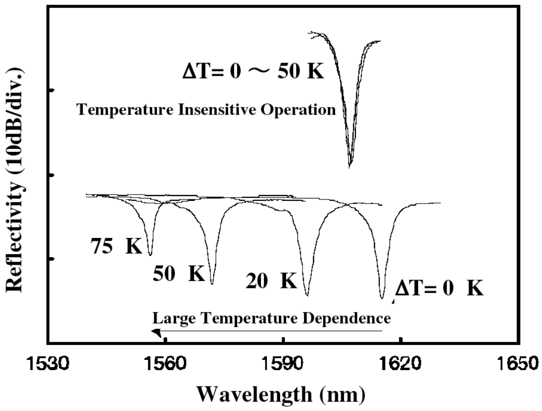


Fig. 14 Temperature dependence of MEMS vertical cavity. [25]

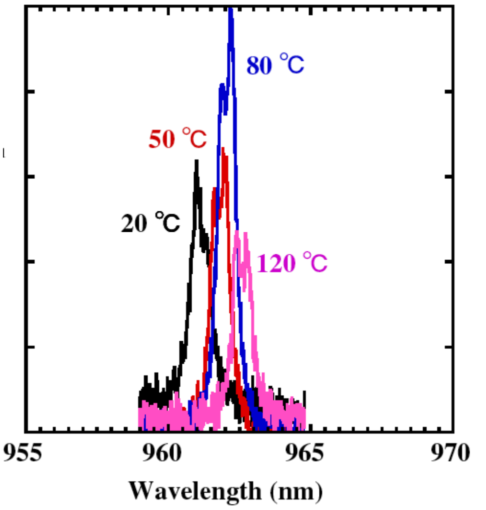


Fig. 16 Temperature dependence of emission spectra. [26]