Recent Progress of Vertical Cavity Surface Emitting Lasers: Wavelength Engineering and New Functions

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ABSTRACT

Vertical cavity surface emitting lasers (VCSELs) have been extensively developed and are now key devices in local area networks based on multi-mode optical fibers. Long wavelength VCSELs are currently attracting much interest for use in single-mode fiber metropolitan area and wide area networks. Also, parallel data links including board-to-board interconnections with low threshold VCSEL arrays are also under development. Low threshold single-mode VCSEL arrays will enable us to realize parallel optical interconnects with low power consumption.

We have developed highly strained GaInAs/GaAs QW VCSELs emitting at 1.1-1.2 μm band. Excellent temperature characteristics have been realized. We present long wavelength GaInAs VCSELs on GaAs substrates, enabling uncooled operation for high speed data transmission in single-mode fibers. Also, we will discuss a possibility of isolator-free operations of single-mode VCSELs. In addition, we demonstrated a single-mode multiple-wavelength VCSEL array on a patterned GaAs substrate for the wavelength engineering of VCSELs. The maximum lasing span of arrays is over 190 nm. Densely integrated multi-wavelength arrays are presented.

Tunable micromachined VCSELs are also attracting much interest for WDM networking, because micromachined tunable VCSELs enable wide continuous tuning. We proposed and demonstrated a micromachined tunable vertical cavity with a strain control layer, which gives us novel functions including temperature insensitive operation, thermal wavelength tuning, and so on. We also propose and demonstrate injection-locked VCSELs for all-optical signal processing. Some results on optical inverters, optical bistable devices and optical regenerators will be reported.

Toward other applications including optical storages and sensing, we will describe metal nano-aperture VCSELs for near-field optics.

Keywords: surface emitting laser, WDM, laser array, optical signal processing, near-field optics

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1. INTRODUCTION

Metro or local 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. A vertical cavity surface emitting laser was invented 25 year years ago. A lot of unique features are can be expected, low power consumption, a wafer level testing and so on. Especially, we are able to expect VCSEL technologies for cost effective solutions.

High speed Ethernets are currently major markets for VCSELs Also, 10G Ethernets will be ready soon. 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 [5-8], GaInAs quantum dots [9] and GaAlInAs/InP [10].

We have developed highly strained GaInAs/GaAs QW VCSELs emitting at 1.1-1.2 μm band. Low threshold and excellent temperature characteristics were realized. Also, the wavelength engineering on VCSELs may give us multiple-wavelength sources and tunable devices. In addition, new functions on VCSELs including optical inverters, and bistable operations have been studied with optical injection locking [11, 12]. In addition, nano-structure VCSELs enables new functions for optical near-field probing [13, 14].

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. We also demonstrate injection-locked VCSELs for all-optical signal processing. Some results on optical inverters, optical bistable devices and optical regenerators will be presented.

Toward other applications including optical storages and sensing, we will describe metal nano-aperture VCSELs for near-field optics and external cavity SHG VCSELs for efficient blue and green emission.

2. Highly Strained GaInAs/GaAs VCSEL

The schematic structure of a 1.2 μm GaInAs/GaAs VCSEL 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 [5-8]. 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 room temperature L/I characteristic of 1.2 μm VCSEL is shown in Fig. 3 [8], exhibiting a single-mode output power of over 2 mW. 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 [15]. Figure 5 shows the eye pattern under 10 Gbps transmission through a 10 km long single mode fiber [8, 15]. The optical feedback sensitivity is an important issue for low cost single-mode LD module. Figure 6 shows the result on single-mode fiber transmission with optical feedback effect. The result shows a potential of highly strained GaInAs VCSELs for use in high capacity networks beyond 10 Gbps [8].

Recently, a monolithic external cavity surface emitting laser (VCSEL) was proposed for increasing the modulation bandwidth [16]. In this structure, the backside of a substrate can be used for external optical feedback. A multilayer-coated concave mirror can be formed on the backside surface of a substrate. Part of the optical output from the VCSEL is injected to the laser cavity after one round trip of the external-cavity. The calculated 3dB modulation bandwidth could be increased from 20 GHz to 32 GHz with out-of-phase coupling of external light. That is attributed to an effective loss modulation induced by optical feedback. If the relaxation oscillation frequency is 20 GHz without optical feedback, the modulation bandwidth can be enhanced to reach at 40 GHz. Furthermore, the simulation of NRZ quasi-random large signal modulation is shown in Fig. 7 [16]. The bit rate is 40Gbps. We show the calculated results of eye patterns of directly modulated VCSELs with and without optical feedback in Figs. 7(a) and (b), respectively. The extinction ratio is 10dB. Pattern-effect can be avoided in the case of with optical feedback. Clear eye opening can be expected with a help of optical feedback.

3. Wavelength Integration 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. [17] We have spent much effort for realizing multiple-wavelength VCSEL array on patterned substrates [18]. 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 [19-21]. 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 [21]. 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 [22]. The wavelength spacing is as small as 0.7 nm as shown in Fig. 11 [22]. Very recently, we achieved 100 channel VCSEL array with separation of 0.1 nm as shown in Fig. 12 [23]. Densely packed array with spatial separation of 20 μm could be achieved. The wavelength engineering of VCSELs may include wavelength tuning and wavelength locking.

4. Optical Signal Processing with Injection Locking

We proposed an injection locked two-mode VCSEL for achieving nonlinear transfer functions as shown in Fig. 13 [11]. An external light from a tunable laser diode was injected through a standard single mode fiber into a 1.55 μm InP-based VCSEL with a 7 μm circular tunnel junction aperture [10], which was fabricated by Nishiyama and his coworkers [10]. The dominant lasing mode at the bias current was the fundamental mode. Figure 14 shows the optical input-output characteristics. The wavelength of the external light was set to be 0.1 nm longer than that of the fundamental mode under free-running conditions. The polarization of the external light was set to be parallel or orthogonal to the dominant lasing mode. Corresponding results are shown as circles and triangles, respectively [12]. In both cases, the coupled output power increased linearly with the input power. The increase of the coupled power was due to the reflection of the input light by the VCSEL. The abrupt switching was observed at a critical input power. This phenomenon would be very similar to that observed in nonlinear etalons. The polarization dependence of the threshold input power was ~ 20 %. The polarization dependence can be reduced by making orthogonal polarizations degenerate. The polarization insensitivity is a unique feature of the VCSEL.

On the other hand, when a high-order mode is injection-locked, an optical inverter function was obtained in Fig. 15. The dynamic behavior of the proposed device with the nonlinear transfer function was investigated. Figure 16 shows (a) the input waveform and (b) the output waveform for an input signal with a 2.5 GHz rectangular waveform [12]. The input signal was successfully converted into a narrow pulse train. The transient response is faster than 100 ps. The proposed device, based on the stimulated emission properties of a VCSEL, could be used as an active nonlinear etalon, requiring lower switching power and offering higher speed operation than conventional nonlinear etalons. The VCSEL structure may provide us possibilities of low power consumption and polarization insensitive operations for all-optical signal processing.

5. Optical Near-field VCSEL

The storage density of conventional optical storages is determined by the spot size of light, which is limited by optical diffraction. One promising way to go beyond the diffraction limit is to use an optical near-field technology. We proposed and demonstrated a metal nano-aperture VCSEL for use in optical recording and readout of data on optical media [13]. The schematic structure of our proposed metal-aperture VCSEL is shown in Fig. 17. The device includes a Au nano-particle in the center of the aperture. The number of the *p*-type DBR pair was designed to be about a half of a standard design for increasing the near-field intensity through the nano-aperture. We formed a 3 μm diameter oxide aperture for single transverse-mode operation. The structure except the top mirror design and the metal nano-aperture is the same as conventional GaAs VCSELs. We inserted a SiO_2 layer underneath the aperture in order to enhance localized-plasmon effect. Our FDTD numerical simulation shows that the nano-particle enables us to excite localized surface plasmon resulting in the enhancement and localization of optical near-field. The thickness of SiO_2 and Au layer is 320 nm and 100 nm, respectively. The diameters of the Au aperture and the Au particle are 400 nm and 100 nm, respectively, which were formed by using focused ion beam (FIB) etching after completing the fabrication of the GaAs VCSEL. The lasing wavelength is 850 nm. We achieved a low threshold current of below 300 μA, showing a possibility of low power consumption in our near-field VCSELs. We obtained single-mode operation in the entire measured current range.

The output power from the nano-aperture was increased by a factor of 1.8 by inserting the Au particle. We measured the localized optical near-field distribution and voltage change by using an experimental setup with a scanning near-field optical microscope (SNOM). Figure 19 shows the measured surface topography (a), optical near-field intensity (b), and voltage change (c) of the nano-aperture VCSEL with a Au nano-particle [14]. The full width at half of maximum (FWHM) of optical near-field distribution is 240 nm and the power density is estimated to be as large as 7.7 mW/μm^2. This is almost 10 times larger than that of our previous measurement [13] and is approaching to an enough power level for optical recording. Nano structure VCSELs may be useful for near-field sensing and recording.

6. CONCLUSION

We developed long wavelength GaInAs 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. We demonstrated a 100-ch high-density multi-λ VCSEL array in 1200nm wavelength band. The small footprint of VCSELs allowed us to form a densely packed VCSEL array both in space and in wavelength. The spatial spacing and wavelength spacing are 20 μm and 0.1 nm, respectively. The wavelength engineering of VCSELs enables us to realize a large-scale multi–λ VCSEL array. We expect that large scale multi-λ VCSEL arrays may open up various applications. We also proposed and demonstrated injection-locked VCSELs for all-optical signal processing. Some results on optical inverters, optical bistable devices and optical regenerators were presented. Metal nano-aperture VCSELs were also demonstrated for near-field optics.

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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. Kondo, M. Arai, T. Miyamoto, and F. Koyama, "Isolator-free, uncooled operation of highly strained 1.1 µm GaInAs/GaAs vertical cavity surface emitting laser for 10 Gb/s single mode fiber data transmission,"OFC2004, Atlanta ,USA, ThD6, Feb. 22-27, 2004.
9. D.L. Huffaker, H. Deng and D.G. Deppe, IEEE Photon. Technol. Lett., 10, pp.185-187, 1998.
10. N. Nishiyama, C. Caneau, G. Guryanov, X.S. Liu, M. Hu and C. E. Zah, "High efficiency long wavelength VCSEL on InP grown by MOCVD," *Electron. Lett*., vol. 39, pp.437-439, Mar. 2003.
11. Y. Onishi and F. Koyama," All-optical regeneration using a vertical-cavity surface-emitting laser with external light injection," IEICE Trans., vol. E87-C, no. 3, pp. 409-415, Mar 2004.
12. Y. Onishi, N. Nishiyama, Catherine Caneau, F. Koyama, and Chung-en Zah, "Nonlinear optical input-output characteristics of 1.55 µm injection-locked vertical-cavity surface-emitting lasers," Appl. Phys. Lett., vol. 84, no. 17, pp. 3247-3249, Apr.2004.
13. S. Shinada, J. Hashizume, and F. Koyama, " Surface plasmon resonance on microaperture vertical-cavity surface-emitting laser with metal grating," Appl. Phys. Lett., vol. 83, no. 5, pp. 836-838, Aug. 2003
14. J. Hashizume and F. Koyama, "Plasmon-enhancement of Optical Near-field of Metal Nano-aperture Surface Emitting Laser," Appl. Phys. Lett., vol. 84, no. 17, pp 3226-3228, Apr.2004.
15. 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.
16. T. Ota, T. Uchida, M. Arai, T. Kondo, F. Koyama, "Enhanced Modulation Bandwidth of Surface-Emitting Laser with External Optical Feedback," 9th OptoElectronics and Communications Conference, OECC/COIN2004, Kanagawa, Japan, 15E1-4, July 12-16, 2004
17. 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.
18. 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.
19. M. Arai, T. Kondo, M. Azuchi, T. Uchida, A. Matsutani, T. Miyamoto and F. Koyama, IPRM 2002, A3-3, Stockholm, 2002.
20. 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.

21. M. Arai, T. Kondo, A. Matsutani, T. Miyamoto and F. Koyama, Device Research Conference 2003,
22. 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.
23. Y. Uchiyama, T. Kondo, K. Takeda, A. Matsutani, J. Hashizume, T. Uchida, T. Miyamoto and F. Koyama, “1.2 μm Band High-density Multiple-wavelength Vertical Cavity Surface Emitting Laser Array”, LEOS 2004, to be presented.

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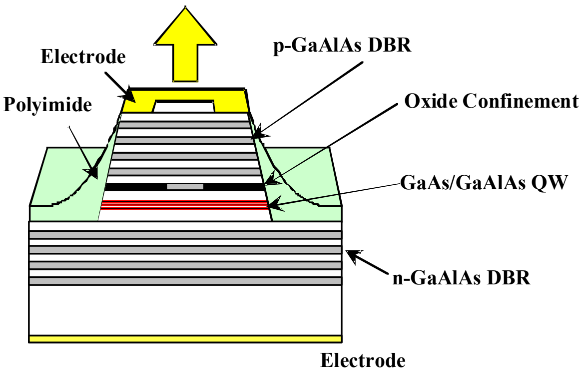


Fig. 1 Schematic structure of GaInAs/GaAs VCSELs. [8]

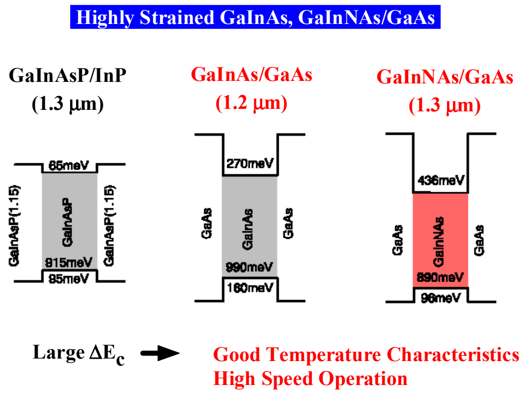


Fig. 2 Band diagram of GaInAs and GaInNAs QWs.

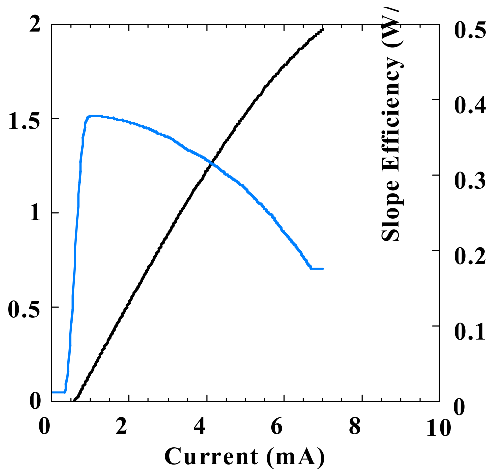


Fig. 3 L/I characteristic of 1.1-1.2 µm GaInAs VCSELs. [8]

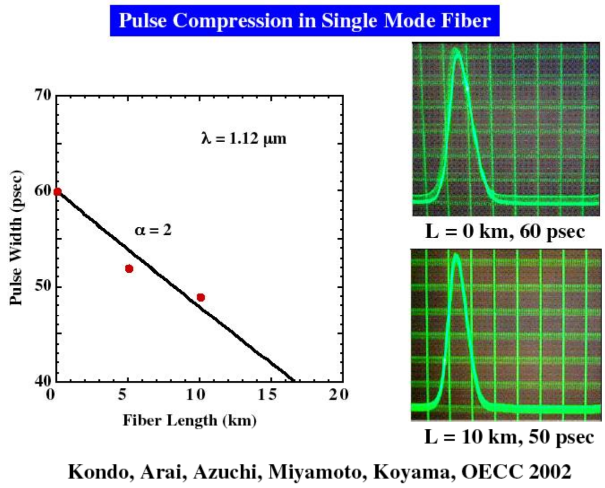


Fig. 4 Pulse compression in 1.2 µm SMF transmission. [15]

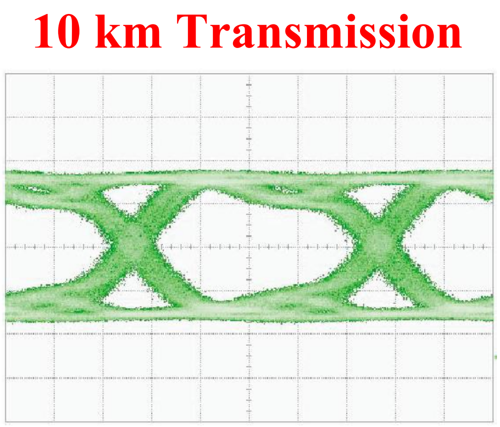


Fig. 5 10Gbps single-mode fiber data transmission [8].

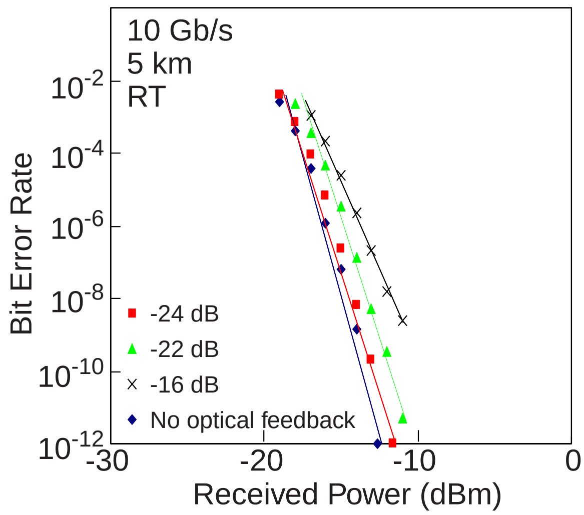
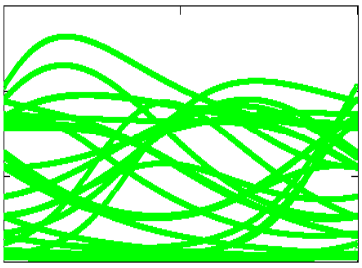
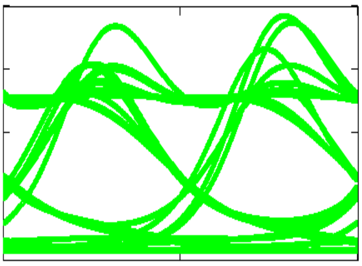


Fig. 6 10Gb/t data transmission using 1.2 µm VCSEL.[8]



(a) without feedback



(b) with feedback

Fig. 7 Calculated eye patterns with and without optical feedback. [16]

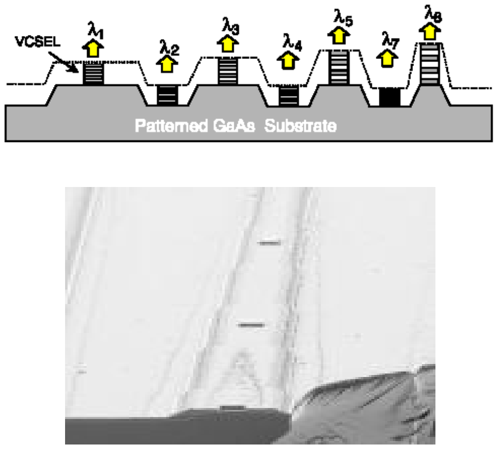


Fig. 8 Schematic of multiple wavelength VCSEL array on patterned substrate.[20]

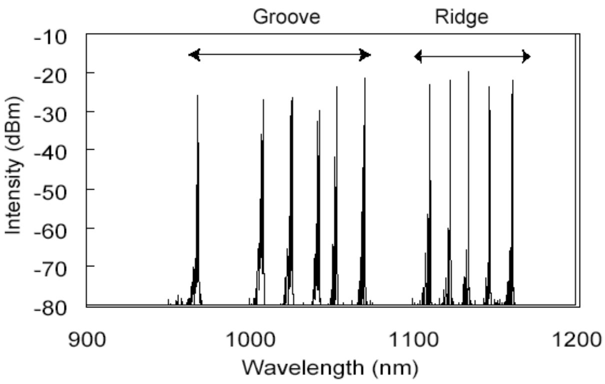


Fig. 9 Lasing spectra of multiple wavelength VCSEL array on patterned substrate.[21]

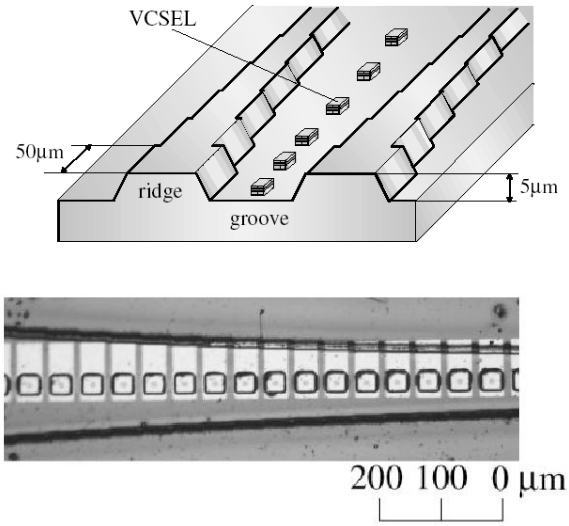


Fig. 10 Densely integrated multi-wavelength VCSEL array. [22]

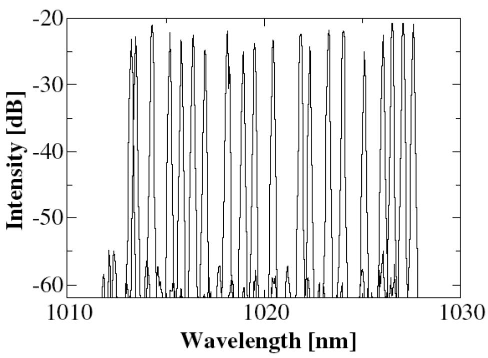


Fig. 11 Lasing spectra of multi-wavelength VCSEL array. [22]

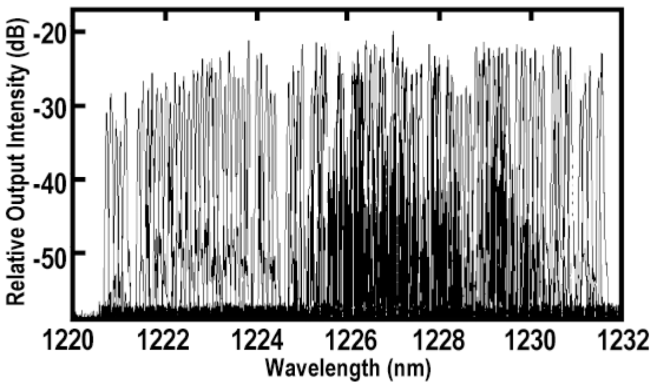


Fig. 12 Lasing spectra of 100 channel VCSEL array. [23]

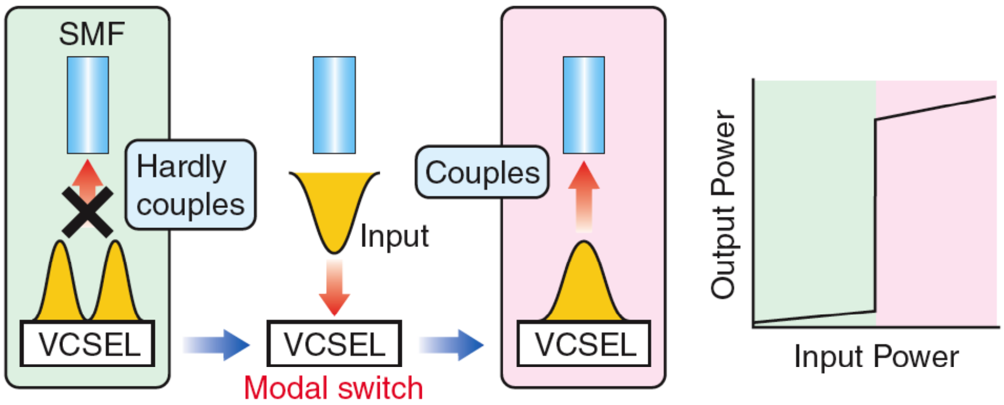


Fig. 13 Injection locked VCSEL for optical signal processing. [11]

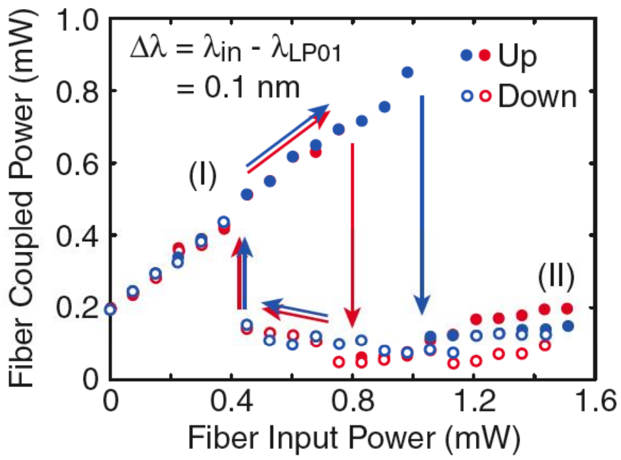


Fig. 14 Input/output characteristic of injection locked two-mode VCSEL. [12]

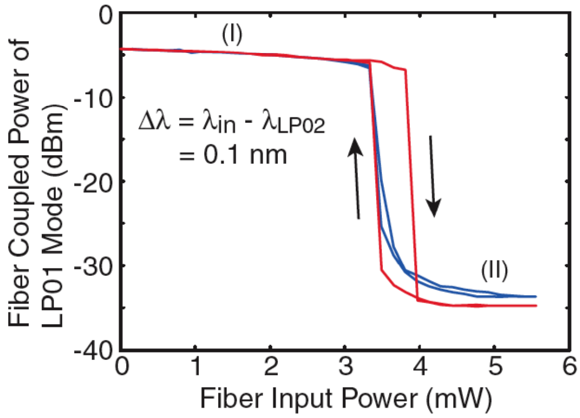


Fig. 15 Optical inverter operation of injection locked VCSEL. [12]

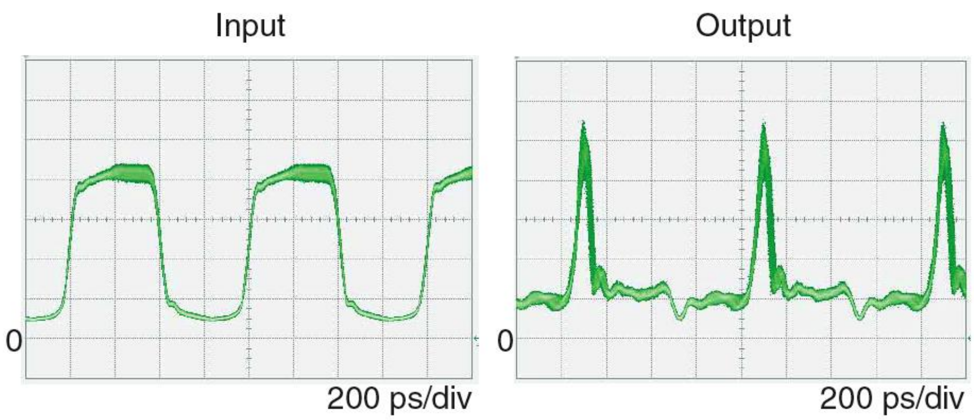


Fig. 16 Dynamic behavior of injection-locked VCSEL. [12]

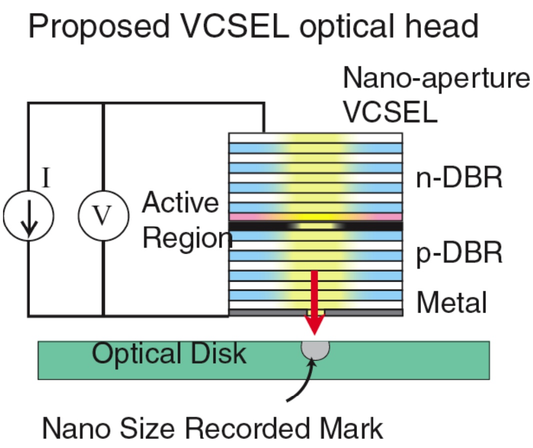


Fig. 17 Metal aperture VCSEL for optical probing. [14]

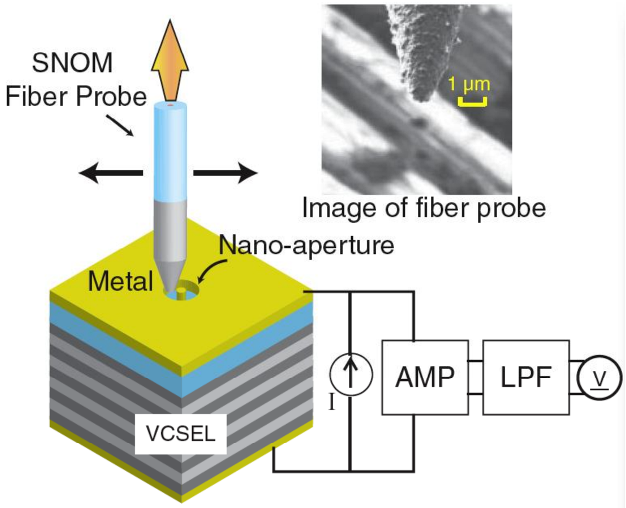


Fig. 18 Experimental set-up for optical probing. [14]

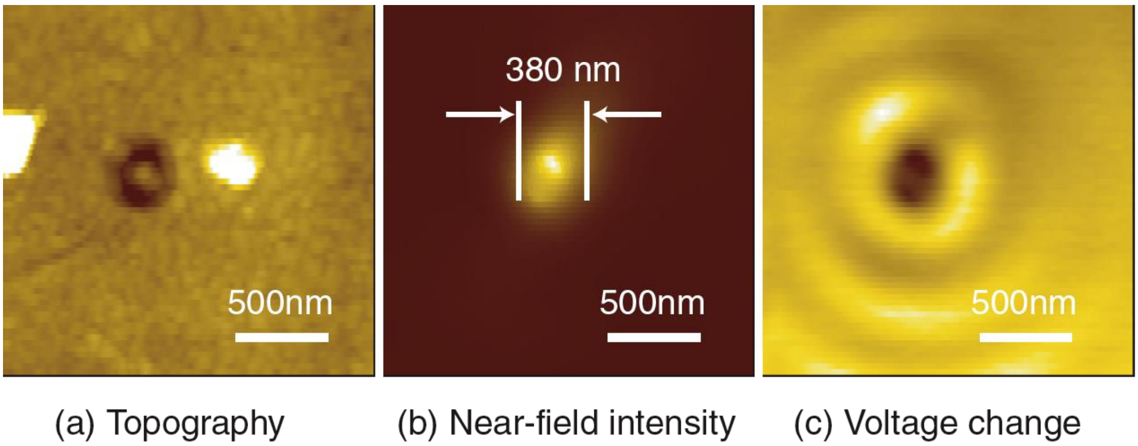


Fig. 19 Measured surface topography (a), optical near-field intensity(b), and voltage change (c) of nano-aperture VCSEL with metal nano-particle. [14]